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Exploring niches for short-season grain legumes in semi-arid Eastern Kenya

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by
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Abbreviations and acronyms

Abbreviation	Description
%	percent
°C	degree Celsius
°Cd	degree days
°E	east
°N	north
°S	south
µmol	micromole
AIR-DRY	(water content at) air dry
ANOVA	Analysis of Variance
APSIM	Agricultural Production System sIMulator
BD	bulk density
BNF	biological nitrogen fixation
C	carbon
Ca	calcium
CERES	Crop Environment Resource Synthesis
CIAT	International Centre for Tropical Agriculture
CLL	Crop lower limit
cm	centimetre
cm^3	cubic centimetre
C	carbon
CO_2	carbon dioxide
CPI	Commonwealth (of Australia) Plant Introduction
CQ	CSIRO Queensland number
CSIRO	Commonwealth Scientific and Industrial Research Organization
CV	coefficient of variation [%]
cv.	cultivar
D	drainage
D	duration
d^{-1}	Per day
DAP	days after planting
DL	dry land
DM	dry matter
DSSAT	Decision Support System for Agrotechnology Transfer
DUL	drained upper limit
EF	model efficiency
e.g.	for example
E_t	water use, evapotranspiration [mm]
et al.	and others
f	flowering
FAO	Food and Agricultural Organization
g	gram

Abbreviation	Description
G x E	genotype environment (interaction)
h	hour
ha	hectare
HI	harvest index [-]
I	irrigation
ID	identification
i.e.	that is
k	extinction coefficient [-]
K	potassium
KARI	Kenyan Agricultural Research Institute
KARLO	Kenya Agricultural and Livestock Research Organisation
KAT	Katumani
kg	kilogram
km	kilometre
l	litre
LAI	leaf area index [-]
LDP	long day plant
LR	long rain
LSD	least significance difference
M	Machakos
m	meter
m^2	square meter
masl	meters above see level
MJ	mega joule
mm	millimetre
N	number of cases
N	nitrogen
N_2	nitrogen (molecular)
Na	sodium
n.a.	not available
NARL	National Agricultural Research Laboratories
NH_3	ammonia
NO_3	nitrate
OC	organic content
p	significance level $p \leq 0.05$
P	phosphorus
P	photoperiod
P_c	critical photoperiod
P_{ce}	ceeling photoperiod
PAR	photosynthetic active radiation
PAWC	plant available water content
pH	1:5 soil: water extract; measure of active hydrogen ion
PO	porosity
ppm	Parts per million

Abbreviation	Description
PS	photosynthetic
Q	Queensland number
R	runoff
R^2	coefficient of determination
RMSE	root mean square error
RUE	radiation use efficiency [MJ^{-1} PAR]
s^{-1}	per second
SAT	saturation
SD	standard deviation
SDP	short day plant
SOILN	ASIM soil nitrogen module
SOILWAT	APSIM soil water module
SR	short rain
t	ton
T	temperature
T_b	base temperature
T_{max}	maximum temperature
$T_{optimal}$	optimal temperature
T_t	thermal time
TE	transpiration efficiency
TSP	triple superphosphate
WUE	water use efficiency [kg ha^{-1} mm^{-1}]
Y	yield

Structure of the PhD thesis

The PhD thesis is divided into an introduction part, followed by four research chapters and a final discussion and conclusion part. The introduction contains a general overview outlining the research topic, a conceptual background as well as a literature review presenting a short overview of the scientific context and basic concepts of the research project. At the end of the introduction part research needs and objectives are highlighted. The research chapters I to IV represent four Journal manuscripts, some of them have been submitted or are in preparation for submission to international peer-reviewed journals. The final discussion and conclusion parts debate the findings from the research chapters in a general context and address the initial research needs and objectives.

Chapter I

The first research chapter Sennhenn, A., Odhiambo, J.J.O., Maass, B.L., Whitbread, A.M. (2015) *"Considering effects of temperature and photoperiod on growth and development of Lablab purpureus (L.) Sweet in the search of short-season accessions for smallholder farming systems"* (accepted at Experimental Agriculture, 24.03.2016) presents the comprehensive analysis of three different datasets, including field and controlled environment studies, to evaluate the photoperiod-sensitivity of potential short-season lablab accessions. The study aims to quantify effects of temperature and photoperiod on growth and development to estimate the possible production success of new short-season lablab accessions in smallholder farming systems in the tropics and subtropics.

Chapter II

The second research chapter Sennhenn, A., Njarui, D.M.G., Maass, B.L., Whitbread, A.M. (2015) *"Understanding growth and development of short-season grain legumes for climate smart agriculture in semi-arid Eastern Kenya"* (in preparation for Journal of Agronomy and Crop Science) presents the fundamental description of growth and development of three short-season grain legumes (common bean (*Phaseolus vulgaris* L.), cowpea (*Vigna unguiculata* (L.) Walp.) and lablab (*Lablab purpureus* (L.) Sweet)) in semi-arid Eastern Kenya. This chapter contains the detailed description and evaluation of field trials conducted at the research station in Machakos, Eastern Kenya.

Agronomic indicators such as biomass accumulation, leaf area index (LAI) and fractional radiation interception as well as the harvest index (HI) and radiation use efficiency (RUE) were quantified with the aim to estimate agricultural production potential of the short-season grain legumes for semi-arid environments.

Chapter III

The third research chapter Sennhenn, A., Njarui, D.M.G., Maass, B.L., Whitbread, A.M. (2015) "*Simulating the growth and development of short-season grain legumes in semi-arid Eastern Kenya*" (in preparation for Agricultural Systems) presents the parameterization and validation of the Agricultural Production System sIMulator (APSIM) legume models for three short-season grain legumes (common bean (*Phaseolus vulgaris* L.), cowpea (*Vigna unguiculata* (L.) Walp.) and lablab (*Lablab purpureus* (L.) Sweet)) in semi-arid environments. Genetic coefficients for parameterization were derived from the field trials as described in chapter II, and validation was realized against the whole dataset from the field trials conducted in Machakos, Kenya. Further, this chapter contains a sensitivity analysis to estimate the impact of key physiological parameters on legume growth such as the extinction coefficient (k), radiation-use efficiency (RUE) and transpiration efficiency (TE). Finally, this chapter presents the results from a long-term simulation experiment to evaluate the yield potential of the different short-season legumes under various management practices in semi-arid Eastern Kenya.

Chapter IV

The fourth research chapter Sennhenn, A., Njarui, D.M.G., Maass, B.L., Whitbread, A.M. (2015) "*Water use and use efficiency of short-season grain legumes in semi-arid Eastern Kenya - coping with impacts of climate variability*" presents the characterization of the variability and agro-climatic changes and associated risks for rainfed crop production systems along the Machakos-Makueni transect in semi-arid Eastern Kenya. This chapter contains the quantification of water-use efficiency of three short season grain legumes (common bean (*Phaseolus vulgaris* L.), cowpea (*Vigna unguiculata* (L.) Walp.) and lablab (*Lablab purpureus* (L.) Sweet)) from measured and simulated data with the aim to evaluate the impact of various soil types to estimate their agricultural production potential in respect to climate variability and risk along the Machakos-Makueni transect in semi-arid Eastern Kenya.

General introduction

The hunger crisis in East Africa in 2011 was an alarming humanitarian catastrophe which refocused the regions efforts on agriculture. Despite this, food insecurity remains high as a consequence of poor rainfall and low fertility soils, both of which directly affect the primarily agriculture based countries. In Kenya for instance, agriculture is the backbone of the economy and the mostly rural population (75 %) depends largely on agriculture for survival (Mora-Vallejo et al., 2008; Muhammad et al., 2010). In addition, the agricultural sector, accounting for 75 % of the total labour force, is dominated by smallholder farmers who produce about three quarters of the regions agricultural outputs (Muhammad et al., 2010). Consequently, strong dependencies result in the linkage between agricultural productivity, economic growth and welfare. Furthermore, the environment plays a key role for the economic development and poverty reduction (WWF EARPO, 2006). Until now, Kenyan poverty rates are among the highest in the developing world (49 % of the urban population and 53 % of the rural population; KNBS, 2010) (FAO, 2015).

There is limited arable land in Kenya with about 80 % of the total land area being arid or semi-arid (ASAL) and further characterized by low soil fertility and limited resources (de Jager et al., 2001; Gachimbi et al., 2002; Macharia et al., 2010). In addition, conditions for the mainly rainfed based agriculture are exacerbated by the highly variable rainfall. Risk management and the improvement of soil fertility as well as water and nutrient use efficiencies are the major challenges in agriculture in semi-arid areas of Eastern Africa including Eastern Kenya (Maingi et al., 2001; Gachimbi et al., 2002). The key strategy for faming survival is the implementation of more resilient dry land systems, which are sustainable and more efficiently utilize internal and external farm resources. One concept, which has been used traditionally by farmers in Eastern Africa is the implementation of crop diversification to cope with the frequent water and nutrient deficits that reduce food security, although this has been neglected increasingly in past (Nguluu et al., 2014). The change from diverse to a maize based farming systems has caused a serious loss in on-farm biodiversity in Eastern Kenya (Kassam et al., 1991; Lenné, 2011; Muhammad et al., 2010). These farming systems are highly susceptible to drought events, challenged by low soil fertility, and require high input levels (Dixon et al., 2001). Urgent improvements are required to increase the efficiency through the design of more resilient farming systems, and ensure food and nutrition security in the view of climate change (Oritz, 2011).

The integration of legumes in maize based dry land farming systems seems to be promising in order to contribute to the on farm diversity and consequently the diversity of food sources with positive impact on food security and health in particular of the subsistence farmers (Bhat and Karim, 2009; Popelka et al., 2004; Pretty et al., 2003). Additionally, diversified maize-legume systems are reported to have a positive impact on yields, soil fertility as well as water and nutrient-use-efficiencies (Searle et al., 1981; Woomer et al., 2004). Factors which have limited the adoption of legume technologies and the introduction of legume species in farming systems include additional labour requirements, market concerns, and the limited access to quality seed material among others (Pretty et al., 2003). Furthermore, the evaluation in respect to climate variability (prolonged droughts and high rainfall variability) of new drought-tolerant legume germplasm and the eco-physiological understanding of their adaption to environmental stresses need to be enhanced in order to identify suitable strategies for low-input farming systems with the aim to maximize their benefits. Crop modelling software, such as the Agricultural Production Systems sIMulator (APSIM), are powerful tools useful in assessing the potential of certain agricultural activities including new crops and management strategies across a range of different environments in respect to future climate scenarios. APSIM applications include farming system design as well as resource management and can have a strong impact in the exploration and identification of niches for promising legumes in smallholder farming systems of semi-arid Eastern Kenya (Keating et al., 2003).

Literature review

Semi-arid Eastern Kenya – a risky place for agriculture?!

Eastern Africa including areas of semi-arid Eastern Kenya is one of the most vulnerable regions to the impacts of climate variability and change (Boko et al., 2007; Challinor et al., 2007; Slingo et al., 2005; Thornton et al., 2011). Statistics on temperature and precipitation patterns reveal that most of Eastern Africa became warmer in the last century and that rainfall exhibits an increased inter- and intra-seasonal variability (Boko et al., 2007; Challinor et al., 2007; Cooper et al., 2008; Cooper et al., 2009). Semi-arid areas of Eastern Kenya are among the most vulnerable regions within Africa, because the resilience on climate sensitive-industries, particularly agriculture is the backbone of their economic development. Economic losses due to the environmental vulnerability have been estimated to cost up to 40 % of the national gross domestic product (GDP) in Kenya (Thornton et al., 2009). Challenges are particularly severe for the small-scale subsistence farmers and in marginal rainfall areas. Additionally to the climatic and environmental challenges, population growth by 2.5 % annually and associated diminution of the average farm size continuously increase the pressure on natural resources and seriously threaten agricultural production and food security in semi-arid Eastern Kenya (Muhammad et al., 2003; Recha et al., 2013). Farm size and population density across semi-arid Eastern Kenya are mainly driven by the availability of water and soils to sustain agriculture. In medium potential areas of the upper midlands, farm size is rather small ranging from 0.5 ha to 1.5 ha, whereas in the low potential areas of the lower midlands farm size is comparatively large: 3 to 5.5 ha compensating for low productivity (Jaetzold et al., 2006). Main crops grown on the mainly family owned farm land are maize, sorghum and legumes (Muhammad et al., 2010). Maize is the most important staple food for the local community, but yields are rather low to fair and beyond their regional potential ranging from 300 to 2,800 t/ha depending on the amount and distribution of rainfall within the growing season, soil type, farm input level, seed material/variety and management practices (Jaetzold et al., 2006; Kassam et al., 1991; Kiome, 2009). Very often maize yields are affected by mid-season droughts common in semi-arid Eastern Kenya and further challenged by low fertility soils and inadequate nutrient inputs. Depending on the agro-ecological potential different cereals (millet and sorghum), legumes, vegetables, fruit crops and livestock have a considerable importance (Recha et al., 2013).

The problem of climate variability

Semi-arid Eastern Kenya covers the Machakos – Makueni transect and forms an environmental gradient of decreasing altitude, increasing temperatures, and decreasing moisture; resulting in a wide range of agro-ecological conditions (Jaetzold et al., 2006). The physical settings (topography and elevation) mainly influence quantity and distribution of rainfall within the area, which is characterized by a bimodal rainfall pattern with two major rain seasons; the so-called ´long rains` (LR) from March to June and ´short rains` (SR) from October/November to February. The amount of rainfall decreases along the gradient from northwest to southeast of semi-arid Eastern Kenya: total annual averages range between 1,300 and 350 mm (Gichuki, 2000). The LR (50 – 300 mm) are usually smaller and less reliable in comparison to the SR (150 – 500 mm) (Karanja, 2006). However, the inter- and intraseasonal rainfall variability is comparatively high in space and time, and droughts are recurrent. Temperature and evaporation rates are generally high as well with mean annual temperatures ranging from 17 to 26 °C (Jaetzold et al., 2006). The analysis of future climate scenarios showed that increased rainfall variability, extended dry spells and increased soil evaporation due to higher temperatures will lead to even more decreased water availability in semi-arid Eastern Kenya in the future (Boko et al., 2007; Stern, 2007). The area recently experienced four successive rain failures - the long and short rains of 2010 and 2011, resulting in 50 - 60 % and 80 - 90 % crop failure in the less dry, and drier zones respectively (Recha et al., 2013). Then again the rain seasons can be extremely wet and often late or sudden, bringing floods causing serious soil erosion damage on arable and non-arable lands (Anyah and Semazzi, 2007). Moreover a general increase in the intensity of high-rainfall events is predicted for semi-arid Eastern Kenya (Christensen et al., 2007). High rainfall variability and increased occurrence of extreme weather events is further aligned with changes in growing season characteristics (Van de Steeg et al., 2009). The start of a growing season has become less reliable, challenging farmers to time their farming activities. Shortened growing periods have additionally increased the demand for adapted crops and cropping system management in semi-arid Eastern Kenya.

As a consequence of the high climatic variation farmers in semi-arid Eastern Kenya tend to use low risk conservative management strategies and usually fail to capitalize the opportunities by better rain season with above average rainfall for instance (Rao and Okwach, 2005). McCown et al. (1991) found that adapted management (fertilizer use and plant density) aligned with precise season prediction could stabilise or even increase maize yield and farm profitability in semi-arid Eastern Kenya.

´Response farming` strategies aim to capture the climate uncertainties in season predictors to adjust agricultural management to weather forecast to enhance the resource use efficiencies and consequently agricultural productivity. However, even if the economic performance of ´Response Farming` is promising the goodness of season predictors in reducing uncertainty is questionable, highlighting the limitations of the response strategies. Precise prediction of rainfall amount and distribution are not possible so far in semi-arid Eastern Kenya, however prediction of season goodness (below or above average) are possible with some certainty (Rao and Okwach, 2005). The design of sustainable and resilient farming systems in the risky environment of semi-arid Eastern Kenya still require climate smart agricultural strategies to cushion the remaining climatic uncertainties.

The problem of declining soil fertility

According to the FAO classification, the most frequent soils in the hilly areas of semi-arid Eastern Kenya are Camisols, Andosols and partly Lithosols and Luvisols; which are of variable fertility, depending on their depth (Jaetzold et al., 2006). In general, these soils are highly susceptible to erosion events due to the topography and ongoing clearing of natural vegetation along hills. The lower midlands of semi-arid Eastern Kenya are dominated by Ferrasols, Acrisols and Luvisols with low natural fertility and very low soil organic carbon content (Barber and Thomas, 1981; Jaetzold et al., 2006). The heterogeneity in soil types results from the inherent soil and landscape variability within Eastern Kenya (Tittonell et al., 2005a). In general, soils are of a porous massive structure characterized by variable water holding capacity depending on soil texture. Many soils have a relatively high sand content resulting in a low water holding capacity and increased erosion susceptibility. These soils fail to accumulate moisture reservoirs to compensate the uneven distributed rainfall within the growing period and further challenge crop growth. The susceptibility to erosion events is, however, highest at the beginning of each growing season, when the land is cleared in preparation to plant new crops and further accelerated by extensive clearing of the natural vegetation for farming purposes (Mora-Vallejo et al., 2008). Additionally to the constraints caused by soil texture, soils in semi-arid areas of Eastern Kenya are characterized by nutrient deficiency and organic matter content (Recha et al., 2013). As in many parts of Sub-Saharan Africa soil fertility management was traditionally based on shifting cultivation, extended fallow periods and the use of external inputs such as animal manure. High population growth has put increased pressure on natural resources and decreased farm

sizes, which further forced the farmers to continuous cultivation and prevent the practice of fallow (Tittonell et al., 2005a). In general, insufficient nutrients are returned to the soil to replace those removed by crop products (Tittonell et al., 2005b). The application of manure or compost is highly variable due to the limited availability and associated labour demand (Tittonell et al., 2005b). The application of other external inputs such as mineral fertilizer is very low as well as the financial resources of the mainly small-scale farmers are limited or fertilizers are unavailable or inaccessible (Gachimbi et al., 2002). Consequently, a continuous decline in soil organic matter and nutrient levels, in particular nitrogen and phosphorus, has been observed in the past, and land degradation has become a significant problem in semi-arid Eastern Kenya (Gachimbi et al., 2002). Besides the application of mineral fertilizer as soil management strategy, nitrogen fixing legumes grown in rotations or as green manure, certain agroforestry (legume) trees, and different organic resources applied to the soil (e.g. compost or manure) or produced *in situ* (e.g., no-tillage systems) are used (Onduru et al., 2001). However, a comparatively large variability in fertilizer use and use efficiencies within single farms is observed in many parts of Eastern Africa (Vanlauwe et al., 2006; Zingore et al., 2007) as well as a rather poor performance of legumes on already degraded soils (Ojiem et al., 2007).

The problem of decreasing diversity

In semi-arid Eastern Kenya as well as the rest of Eastern Africa, highly diverse plant types and varieties (landraces and bred lines) and animals are available (Kassam et al., 1991; Nguluu et al., 2014). Evidence from the field, however, indicates that the use of agrobiodiversity in these regions has declined over the last decades (Lenné, 2011; Muhammad et al., 2010). This could be in response to a combination of factors including declines in soil fertility (Fermont et al., 2008), changes in climate (Thornton et al., 2011), market failure and lack of available germplasm (Nagarajan et al., 2007), disease and pest pressures (Lenné, 2011) and lack of knowledge and ineffective extension or seed systems (Nagarajan et al., 2007). The trend of declining agrobiodiversity and shift to intensive maize cropping systems in semi-arid Eastern Kenya (Muhammad et al., 2003) has negatively affected the food production system and the environment, as biodiversity can contribute directly to food security, nutrition and well-being of rural communities by providing a wide range of plant and animal products (Lenné, 2011). Additionally, biodiversity is of great importance to maintain ecosystem services (Jackson et al., 2009; Nguluu et al., 2014). Furthermore, (crop) diversification has been a key strategy for smallholder farmers to manage climatic and market risks (Schiere et al., 2006) as

different crops vary in their response to cold, heat or drought, or susceptibility to pests and diseases (Recha et al., 2013). The application of cropping strategies that increase biodiversity such as inter-cropping of legumes with cereal crops, for instance, can contribute to improving soil fertility, reducing soil erosion, and reducing persistence of pests and diseases on the farms (Recha et al., 2013).

Benefits of grain and dual-purpose legumes in smallholder farming systems

Legumes are one of the most important crops in agricultural systems all over the world including semi-arid Eastern Kenya. Almost 15 % of the Earth's arable surface equal to about 180 Million ha is dedicated to grain and forage legume production (Graham and Vance, 2003). Grain legumes are of great importance for the human diet, accounting for 33 % of the dietary protein nitrogen (N) needs of humans (Vance et al., 2000). The major grain legumes used by humans include common bean (*Phaseolus vulgaris* L.), pea (*Pisum sativum* L.), chickpea (*Cicer arietinum* L.), broadbean (*Vicia faba* L.), pigeonpea (*Cajanus cajan* L.) and cowpea (*Vigna unguiculata* (L.) Walp.). Grain legumes such as soybean (*Glycine max*) and peanut (*Arachis hypogeae*), provide more than 35 % of the world's processed vegetable oil. In addition to the importance in order to fight the world's food and nutrition insecurity, legumes are important components in agricultural systems because of their ability to fix atmospheric nitrogen. Biological nitrogen fixation (BNF) is a unique feature, which makes legumes highly valuable for soil improvement and sustainable intensification of agricultural systems (Graham and Vance, 2003; Onduru et al., 2001). Evidence suggests that associated cereals may benefit through N transfer from legumes in mixed cropping systems were N is limited and the access to external inputs such as mineral fertilizers is restricted (Fujita et al., 1990). Furthermore, legumes used in small-scale farming systems have traditionally enabled farmers to cope with erosion as well as declining levels of soil organic matter and available N. Since soil erosion and declining soil fertility are the major constraints in most of sub-Saharan countries, legumes can improve farm productivity in smallholder agriculture as short time fallows and green manure (Mureithi et al., 2003). Moreover, legumes can provide a good ground cover, suppress weed growth, reduce the raindrop impact and runoff, especially in hilly areas, and break pest and disease cycles in cereal-based farming systems (Lal et al., 1991). Besides their importance and advantageous attributes, legume production has not kept pace with the improvements in cereal yields.

Problems associated with climate change, such as increased drought events and increased rainfall variability, are likely to worsen the situation because of the projected rapid expansion of water stress (Postel, 2000). Increased drought tolerance in grain legumes is of crucial importance in order to adapt yields to future demands. However, legumes display great agro-morphological diversity with promising potential for challenging environments.

Common bean

Common bean also referred to as dry bean is by far the most important food legume in the world. It is produced in diverse production systems in almost all continents covering a wide range of agro-ecological environments including areas of Africa and Latin America. In many African countries including Kenya, Tanzania, Malawi, Uganda and Zambia common bean is the major source of protein in local diets (Maingi et al., 2001). Moreover, common bean provides valuable nutrients, including folic acid and iron, and has generally good nutritional properties. Grains of common bean are further highly appreciated in the developing world because of their great eating and cooking qualities and long storage capabilities (Singh at al., 2006). Additionally, dry husks are fed to animals or used as fuel for cooking in many parts of Sub-Saharan Africa (Jones, 1999). In these regions as well as in Latin America, common bean is mainly cultivated in smallholder farming systems with limited inputs as it is a traditional subsistence crop. They are grown in sole stands or in diverse inter-cropping systems (Maingi et al., 2001). About 25 million ha were estimated to be under common bean cultivation worldwide producing approximately 20 million tons per annum (between 2006 and 2008 according to Akibode and Maredia, 2011). Average yields recorded, however, remain very low in particular in Sub-Saharan Africa were grain yields rarely exceed 0.5 t ha^{-1} under stress conditions with limited available inputs (Akibode and Maredia, 2011). Losses due to pests and diseases are comparatively high if grown in smallholder farming systems, as pesticides are usually not applied at appropriate levels. However, common bean diversity is known to be among the highest observed for food crops around the world with tremendously high levels of variation in growth habit, seed and maturity characteristics (Jones, 1999). Its adaption to a wide range of environmental conditions favours its application in diverse and heterogeneous small-scale farming systems of the tropics and subtropics. Furthermore, common bean is adapted to a wide range of temperature and rainfall regimes (Acosta Gallegos and Kahashi Shibata, 1989).

Cowpea

Cowpea is one of the most important food and forage legumes in the tropical and subtropical world and it is known under a variety of (local) names, including blackeye bean or blackeye pea. It is cultivated in parts of Asia, Africa, Southern Europe and Southern United States of America as well as in Central and South America (Timko and Singh, 2008). Cowpea provides the major source of dietary protein, particularly in the developing world, and plays an important role for the livelihoods of millions of households as it nutritionally complements typical low-protein cereal or tuber-based diets (Singh at al., 2006). The seeds contain about 20 – 30 % protein and are a rich source of minerals and vitamins including high contents of folic acid (Hall et al., 2003). But not only the grains are consumed, leaves are a highly valued component of the local diet as they provide additional minerals and, therefore, are of significant nutritional importance in many parts of Africa and Asia (Hall et al., 2003). However, only the dry grain production of cowpea can be estimated worldwide, with about four million tons produced on approximately 10 million ha (Timko and Singh, 2008). Most important cowpea production areas include drier Savannah and Sahelian zones of Central and West Africa, where it is mainly grown in inter-cropping systems in association with cereal crops such as millet, sorghum and maize or tuber crops like cassava (Singh and Tarawali, 1997). Other important production areas are lower elevation areas of Eastern Africa, for instance (Timko and Singh, 2008). Cowpea refers to warm-season annual crops and requires minimum temperatures of 18 °C throughout the growing period. Its performance is, however, optimal at temperatures of 28 °C and it is known to perform comparatively better than other legumes at high temperatures (Craufurd et al., 1997). But even if cowpea is known to have a relative good adaption to drought stresses and cowpea production is documented in Sahelian environments with low humidity, low water availability is the most important abiotic constraint for its production success. Growth and yield are substantially suppressed under dry conditions (Hall et al., 2002, 2003). Advantageous is, however, its performance on soils with comparatively low soil fertility, particularly in smallholder farming systems of Sub-Saharan Africa. Furthermore, its nitrogen fixation rates are known to be relatively high and cowpea tolerates a wide range of pH compared to other tropical grain legumes. Therefore, its integration in rotation systems to restore soil fertility is highly valued among small- holder farmers (Sanginga et al., 2003). Despite abiotic production constraints, the major problem for cowpea cultivation in Sub-Saharan Africa are insect pests including aphids, thrips, bod borers, pod-sucking bugs and storage weevils, which cause significant production losses, particular in resource-poor smallholder farming systems, where pesticides are economically inaccessible (Singh and van Emden, 1979).

Lablab

Lablab purpureus (L.) Sweet is also known as Hyacinth bean, Egyptian kidney bean or Dolichos. Lablab refers to an ancient domesticated crops nowadays widely distributed not only in Africa, its origin; but widely cultivated throughout the Indian sub-continent and Southeast Asia (Smartt, 1985; Maass et al., 2005; Maass, 2006; Kimani et al., 2012). Even if its diversity is comparatively high in South-Asia, Africa is the only continent where it is native in some areas (Maass et al., 2005, 2010). In general, lablab is suitable for cultivation throughout the tropics and subtropics from sea level up to 2500 m asl. It has been recorded in areas with 200 to 2500 mm of annual rainfall and temperatures between 18 and 30 °C, the minimum required temperature for growth is, however, 3 °C and high temperatures have shown to affect growth and development (Duke et al, 1983; Hill et al., 2006; Maundu et al., 1999). Lablab offers great agro-morphological diversity, and forage and grain types are available, including different growth types as well as annual and perennial varieties (Maass et al., 2005). As a multi-purpose legume, lablab is used for human consumption, as a fodder crop for livestock, as a rotational and cover crop as well as a pioneer species to improve soil fertility and soil organic matter content of degraded soils (Karachi, 1997; Hill et al., 2006). Lablab is highly valued for human consumption as not only the seeds are eatable, but also young leaves or green pods are traditionally eaten as African vegetables (Pengelly and Maass, 2001; Kimani et al., 2012). Thereby, lablab is used in mixed or mono-cropping systems, as part of home gardens or in crop rotation systems (Maass et al. 2010). In inter-cropping systems, lablab is cultivated in association with millet, groundnut, sorghum or maize (Hill et al., 2006; Kimani et al. 2012). In summary, the multi-purpose crop is a traditional African vegetable with an unexploited potential for smallholder farming systems in semi-arid areas in the view of climate change (Maass et al., 2005, 2010) as its adaption to drought environments is better than observed in common beans or cowpea (Maundu et al., 1999; Piper and Morse, 1915). Despite its long tradition, large agro-morphological and physiological diversity and adaption to a wide range of different and difficult environments and nutrient stresses as well as its suitability for various agro-ecological zones (AEZ), especially semi-arid environments, its use decreased dramatically in Eastern Africa during recent years (Ngailo et al., 2003). Due to the previous discouragement of lablab cultivation in favour of common beans by the colonial authorities in Kenya (Robertson, 1997), today lablab is referred to be underutilized or even a ´lost crop` (Maass et al., 2010) due to limited access to quality seed material and the lack of information and extension (Pengelly et al., 2003).

This has led to the threat of genetic erosion of naturally occurring and semi-domesticated lablab varieties in Africa over the last decades (Maass et al., 2010). Additionally, increased labour requirements for its management, in particular for harvest and grain peeling (Duke et al., 1983); poor flavour attributes and cooking qualities of some grain lablab genotypes may have led to a decreased utilization and favoured the use of other legume species, in particular for human consumption (Smartt, 1985; Pengelly and Maass, 2001; Maass et al., 2010).

Physiological concepts of resource use efficiency

Resource capture and resource use efficiency are fundamental concepts to design strategies for climate smart agriculture in resource-constrained environments, hence, the quantification of resource use is essential to better understand plant environment interactions (Black and Ong, 2000). De Wit (1992) comprehensively analysed the interactive affects to be considered to quantify resource use efficiency in agricultural systems and concluded that Liebscher's Law of the Optimum best described the growth responses. De Wit (1992) postulated that resources are utilized most efficiently when their supplies are all close to yield-optimizing levels. Functionally of synergies however can examined at different scale. To quantify growth and development, two major concepts of resource capture are applied; first, the thermal time model to describe the effects of temperature on development and second, the relationship between accumulated intercepted solar radiation and accumulated biomass (Monteith, 1977).

Thermal time

The thermal time concept describes the rate of plant development as a function of temperature between a range of cardinal temperatures related to cumulative heat (T_t, °Cd). Subsequent is the relationship described to be linear between the base temperature and the optimum temperature. At the optimum temperature, developmental processes proceed at their maximum speed. From the optimal temperature towards the maximum temperature, the rate of developmental processes follows another linear but declining relationship. Below the base temperature and above the maximum temperature no development is observed (Monteith, 1977). These relationships have been observed in several studies on (sub)-tropical as well as temperate species. For that reason, this concept was applied very successfully to determine phenological responses of various plant species across different environments (Black and Ong, 2000).

Light

Under non-stressed environmental conditions, the amount of dry matter produced by a crop is linearly correlated to the amount of solar radiation, in particular photosynthetic active radiation (PAR), intercepted by the crop. The final quantity of radiation intercepted depends on the amount received by the canopy (canopy architecture and growth habit), the duration (phenological development) and fractional interception (Blum, 2005). The efficiency of the conversion ability of a crop; described as the quantity of biomass produced per unit intercepted radiation is defined as the radiation use efficiency (RUE, g MJ^{-1}) being the slope of the regression line (Monteith, 1977). Radiation interception is highly variable for different crops and different phenological stages throughout the growing period depending on the actual green leaf area and the extinction coefficient (k) (Sivakumar and Virmani, 1984; Thompson and Siddique, 1997; Watiki et al., 1993). The extinction coefficient describes the capability of the canopy to intercept light depending on morpho-physiological conditions (biomass partitioning, leaf angle, spatial and optical attributes of the leaves, among others) (Black und Ong, 2000). Radiation interception is, therefore, not only a matter of genetic make-up alone, but, in fact, influenced by environmental factors (Jeuffroy and Ney, 1997). Water stress, for example, was reported to cause a reduction in RUE in many studies of grain legumes (Craufurd and Wheeler, 1999; Muchow, 1985; Tesfaye et al., 2006). Therefore, parameters such as k and RUE can be used to evaluate crop performance and yield limitations of various legumes to estimate their potential for different farming systems and climatic conditions.

In terms of light, not only quantitative considerations are important to determine crop growth and development, but qualitative considerations are of great interest as well. Photoperiod, for instance, is a major determinant of the phenological development of plants and matching crop phenology to environmental and climatic conditions is a key strategy for efficient resource use in agricultural systems, in particular in semi-arid areas (Black and Ong, 2000). In (sub)-tropical farming systems, a major challenge is to align crop life cycle with season (Imaizumi and Kay, 2006). Therefore, triggering the switch from vegetative to reproductive growth phase is critically important and of great interest for agronomists and plant breeders, since flowering transition directly influences the reproductive success (Putterill et al., 2004).

Water

In semi-arid environments, including the semi-arid Eastern Kenya water is the most limiting factor for agricultural production (Passioura, 1996; Passioura and Angus, 2010). The understanding of crop water use and use efficiency is essential in order to increase crop productivity and agricultural profitability in these areas. To compensate for the impacts of climate change, improved agricultural systems need to be designed to decrease the pressure from the existing water resources and improve quantity and quality of agricultural production in order to ensure food security in the future. The crucial importance of water for agricultural production is implemented in the concept introduced by Molden et al. (2003): ´more crop per drop`. They advised to consider crop production in terms of production per unit water rather than per unit land only. The effective water use and the water use efficiency (WUE) are major targets of crop yield improvement under drought stress (Blum, 2009). Therefore, an adequate quantification of water use in agricultural systems is necessary including the determination of water losses. Almost 99 % of water used in agriculture is lost as evapotranspiration (E_t), defined as the sum of water loss by evaporation from the soil and transpiration through the crop canopy (Rana and Katerji, 2000). In the praxis, there are several direct and indirect methods available to measure and quantify E_t, including hydrological, micro-meteorological and plant physiology approaches (Rana and Katerji, 2000). The hydrological approach, often used for the analysis of field and simulation experiments, is an indirect method based on the principle of the conservation of mass:

$$E_t = \Delta W + P + I - D - R.$$

Where ΔW is the change in soil water stored over the period considered, P is the precipitation and I is the amount of irrigation applied, while D and R are losses from the system through drainage and runoff. WUE is then defined as the ratio of accumulated biomass production or grain yield and E_t expressed in kg mm^{-1} ha^{-1}. Finally, the productivity in respect to water depends on several factors, such as crop genetics, soil characteristics, water-management practices, agronomic practices, economic policies, and production incentives. It integrates the expertise of crop scientists, breeders, irrigation engineers, planners, and economists (Singh et al., 2014). Of fundamental importance is the understanding of the (physiological) drought response mechanism of crops and their varieties. To evaluate this, different measures and concepts have been introduced in the past. The potential yield increase in specific environments through the proper exploitation of locally better adapted genotypes seems to be a promising strategy for production improvement.

Unfortunately, little effort has been put in the enhancement of understanding the physiological basis of genotype x environment (G x E) interaction in regard to water stress (Turner et al., 2001). In respect to drought tolerance, physiological adaption mechanism and their interaction to plant morphology are very complex. The definition of the drought-resistant ideotype per se is multifaceted (Blum, 2005). However, phenology is one of the most important factors influencing adaption and yield in annual crops. Matching crop phenology to environmental and climatic conditions, primarily water supply is a key issue for efficient resource use (Passioura and Angus, 2010; Turner et al., 2001). In many tropical and subtropical farming systems, a major challenge is to align crop life cycle with season in particular in respect to water availability (Imaizumi and Kay, 2006). The genetic variation in crop growth duration, for example, is generally large in crops; this is particularly true for indeterminante species such as grain legumes (Turner et al., 2001). Furthermore, the differentiation between drought avoidance and drought resistance is important for the evaluation of the drought stress response of different legume species and varieties. In the ´Drought-Resistance Framework` introduced by Turner et al. (2001), they distinguish between drought escape, dehydration postponement and dehydration tolerance in respect to drought resistance and propose these as possible targets for yield improvement, in particular for semi-arid cropping systems.

Yield concepts for sustainable intensification

The aim of sustainable agricultural intensification is to maximize food production from the existing farmland, while minimising the pressure on the environment. This concept holds promise to play a fundamental role to ensure food security, while protecting our natural resources in a world where the continuing population growth and changes in living standards and consumption constantly increase the demand for agricultural products, including food, fodder, fibre and bio-fuels (Bindraban and Rabbinge, 2012; Foley et al., 2011; Godfray et al., 2010). Increasing productivity and resource use efficiency of agricultural systems is, therefore, of crucial importance and subject of agricultural research and extension worldwide (Garnett et al., 2013; Keating et al., 2010). Concepts applied to develop strategies for sustainable intensification include the consideration of site-specific potential, attainable and actual yield levels (Figure 1), which allow to determine and analyse yield gaps (van Ittersum and Rabbinge, 1997). Potential yield is defined as the yield of a crop when grown under favourable conditions, only dependent on solar radiation, temperature and CO_2 concentration, without any abiotic or biotic growth limitations from water, nutrients, pests or diseases.

In rainfed agricultural productions systems, including the majority of small-scale farming systems of semi-arid Eastern Kenya, crop yields are however often limited by the availability of water and nutrients. Consequently, water-limited or attainable yield as such is defined as the yield level reached under rainfed conditions without growth limitations from soil nutrient constraints or pests and diseases.

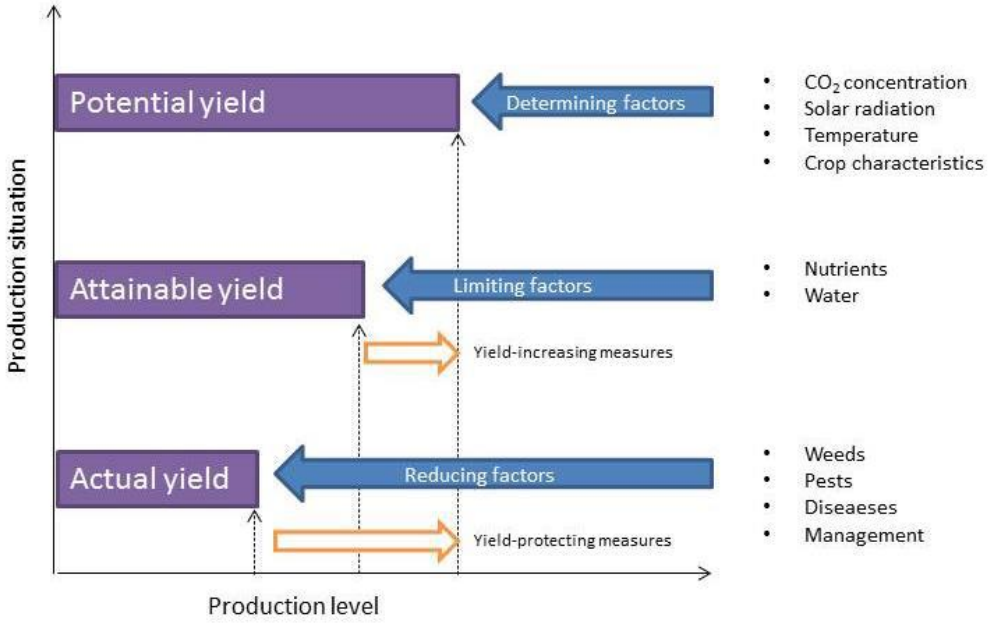

Figure 1: Yield gap concept after van Ittersum and Rabbinge (1997).

Finally the yields reached on farmers field equal the actual yield and present the corresponding yield levels under consideration of current management practices and the impact of weed pressure as well as pests and diseases (Lobell et al., 2009; van Ittersum et al., 2013). The yield gap analysis targets to identify and quantify the differences between the different production levels. They represent the gap between actual statutus and the improved situation. Furthermore yield gap analyses are relevant in order to assess the resource use efficiency of different agricultural production systems (Keating et al., 2010). In agricultural systems of Africa, including semi-arid Eastern Kenya, yield gaps are profound; potential and attainable (water-limited) yields as well as actual yield levels show high temporal and spacial variation (Tittonell and Giller, 2013). The major reason for the continuing large yield gaps in Africa are the limited availability of water, in particular in semiarid environments, and the lack of available inputs such as nutrients (Keating et al., 2010). The importance of genetic, environmental and management factors for the different production levels differ; the impact of crop genetic determinates decreases from potential to actual yield levels, whereas the influence of management strategies increases towards actual yields (Figure 2).

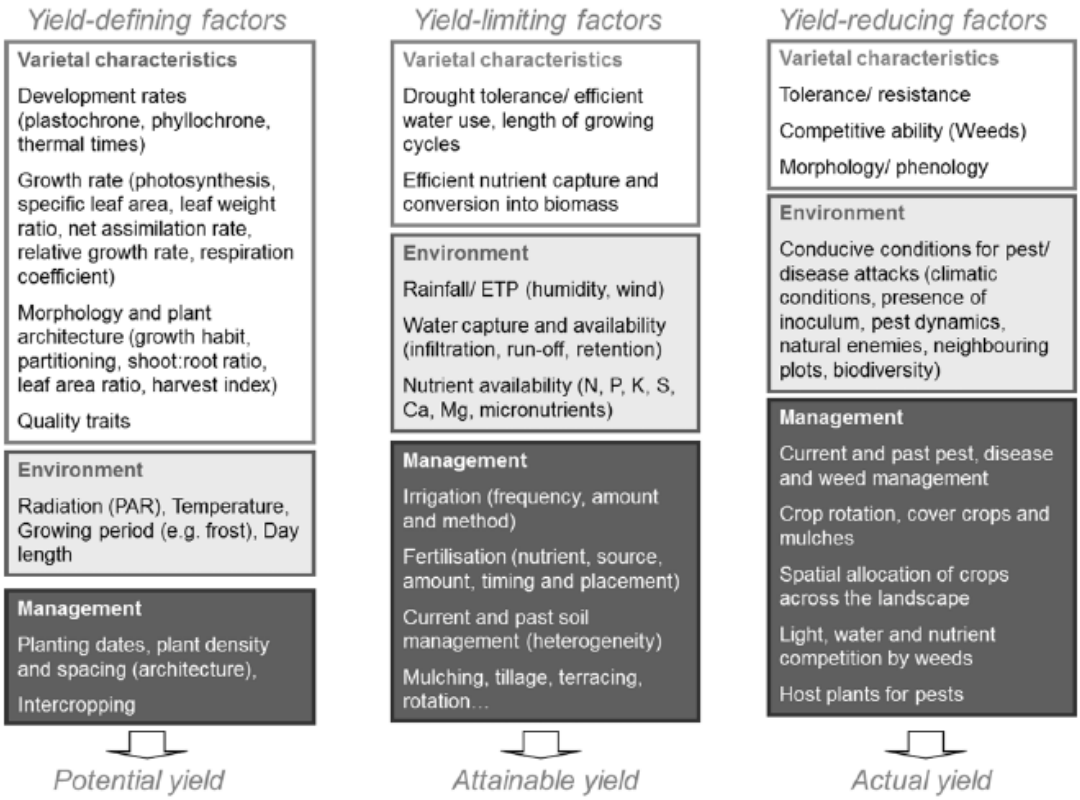

Figure 2: A summary of yield-defining, yield-limiting and yield-reducing factors determining, respectively, the potential, attainable and actual yield levels with factors grouped into varietal characteristics, uncontrolled environment and management (Tittonell and Giller, 2013).

In semi-arid areas, crop yields are typically limited by water availability. Agricultural interventions target to minimize the yield gap between water-limited potential yield and actual yield through adequate variety selection (genetic component), a better allocation of resources (environment component) and suitable management (Lobell et al., 2009).

These include breeding or management interventions, which target to increase the potential water supply and the share of the water transpired, as well as the increase of the transpiration efficiency and biomass partitioning towards grain production (Passioura and Angus, 2010). This concept is implemented in the function:

$$Y = T \times TE \times HI$$

Where Y is yield, T is water transpired, TE is transpiration efficiency for producing biomass and HI is harvest index (Passioura and Angus, 2010). Or expressed as a function of water use (WU) and WUE:

$$Y = WU \times WUE \times HI.$$

These concepts highlight the priority to consider water productivity and a crop´s water balance in semi-arid crop production systems and was described as the ´Yield Component Framework` (Passioura, 2006; Turner et al., 2001). The subcomponents of this relationship often interact and are partly influenced by each other, representing an integrated function of a number of phenological, morphological, physiological and biochemical determinants. They are, however, considered independent enough to be treated separately. Figure 3 illustrates factors influencing water-limited potential yield as a diagnostic framework to identify drivers for the large gaps usually observed between water-limited potential yield and actual yield in semi-arid areas (Passioura and Angus, 2010). The major losses in semi-arid areas are soil evaporation (60 – 80 % of the annual rainfall) and runoff, (especially in the hilly areas of Eastern Kenya) and management interventions need to target these losses to increase WUE and TE (Whitbread et al., 2015).

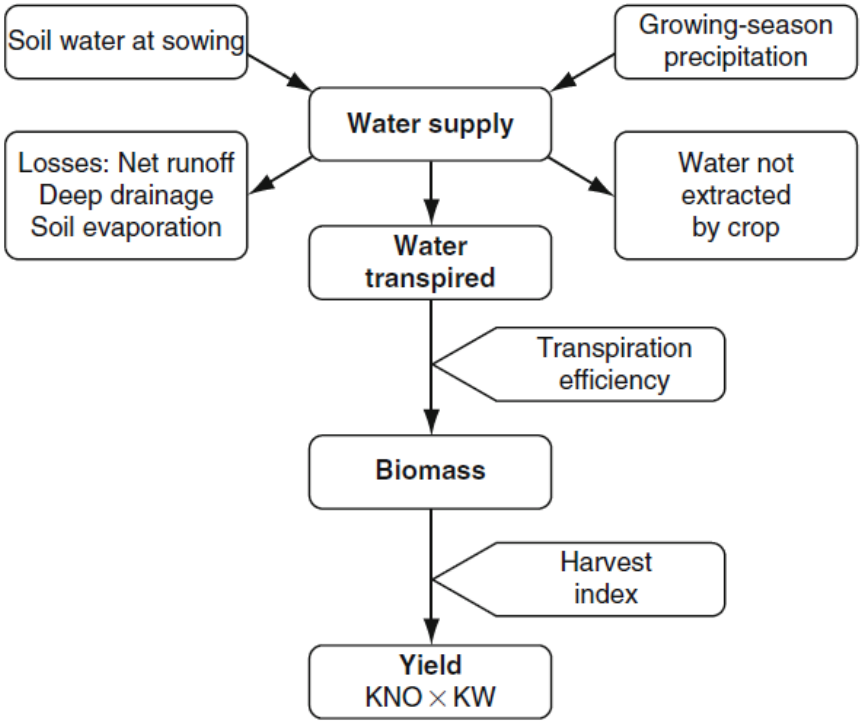

Figure 3: Schematic illustration of main variables and processes involved in generating grain yield from limited water supply. Also included is an alternative dissection of yield into number of grains per hectare (KNO) and mean kernel weight (KW) (Passioura and Angus, 2010).

Crop modelling for farming system analysis in semi-arid areas

Smallholder farming systems in Kenya, for instance, are highly diverse, spatially heterogeneous and dynamic (Tittonell et al., 2007), and agricultural interventions, which target to maximize actual crop yields and close yield gaps, need to consider the multi-dimensional character of these systems. Methodological approaches, including system analysis through simulation modelling, aim to evaluate options for sustainable intensification of farming systems and, at the same time, manage to consider their diversity as well as spatial and temporal variability (Tittonell et al., 2005a; Tittonell et al., 2005b; Whitbread et al., 2011). Simulation models accomplish to address the complexity of smallholder farming systems, which is difficult to capture through classical agronomical experiments alone (Holzworth et al., 2014; Robertson et al., 2001; Whitbread et al., 2010). Furthermore, their application allow to scale up effects of agricultural intervention and strategies in space and time considering different production levels and scales. Thereby, simulation models are able to perform prospective or explorative research through the *ex-ante* assessment of the potential impact of internal and external factors, including site and crop selection considerations, management strategies or the evaluation of climate change effects (Carberry et al., 2002; Cooper et al., 2008; Tittonell and Giller, 2013). However, it is important to keep in mind that all models are only simplifications of the reality. They do not aim to mimic reality in great detail and focus on different scales. Usually, the research question or application purpose determines the degree of complexity necessary. Therefore, the model choice is always a compromise between complexity and applicability under consideration of the application focus reaching from large scale management-based to more detailed process-orientated scales.

One of the most applicable models to better understand plant growth and development in response to environmental and management factors at field level has been the Agricultural Production System sIMulator (APSIM) framework (Holzworth et al., 2014; Keating et al., 2003). APSIM consists of a modular modelling framework including plant, soil and management modules. It was developed to simulate biophysical processes in farming systems in particular crop growth and development upon incoming radiation limited by temperature stress, water supply and N availability (Holzworth et al., 2014). Moreover, APSIM has proven to simulate key soil and crop processes in resource-constrained and risky environments of smallholder farming systems in semi-arid areas, including Eastern Kenya, as it manages to address primary challenges and limitations such as inter- and intra-seasonal rainfall variability as well as the variation in crop response to soil types and agronomic management (Whitbread et al., 2010).

Another process based model framework which operates on plot scale and is widely applied in the tropics is the Decision Support System for Agrotechnology Transfer (DSSAT) (Jones et al., 2003). DSSAT is a rather a collection of several model which are connected though the decision support system. The model aims to simulate growth and development as well as yield of monocrop production systems under various management options in consideration of soil water, carbon and nitrogen dynamics as well as weather and genetics (Jones et al., 2003). The revised cropping system model DSSAT-CSM contains models for 16 crops (maize, wheat, soybean, peanut, rice, potato, tomato, dry bean, sorghum, millet, pasture, chickpea, cowpea, velvet bean, brachiaria, grass, and faba bean) (Jones et al., 2003).

Research needs and conceptual framework

The rapid human population growth and increasing demand for agricultural products, including food and fodder, is putting pressure on agricultural production systems and environmental resources. Sustainable intensification aims to maximise primary production with effective resource use under consideration of ecological processes which contribute to regulate the productivity in agroecosystems (Tittonell and Giller, 2013). Even if food production from smallholder farming systems is the backbone of global food production, large yield gaps are widespread, in particular in African smallholder farming systems. Moreover, many semi-arid farming systems are becoming less diverse, and consequently, less resilient and nutritionally secure (Lenné and Wood, 2011; Tscharntke et al., 2012). However, particularly resource-constrained agricultural systems strongly rely on biodiversity and associated ecological processes (e.g. stress-adapted crop types, integrated soil fertility management) (Jackson et al., 2007). A ´The paradox of scale` or the ´inverse farm size-productivity relationship` - concepts, which are controversially discussed among economist, agronomist and ecologist - further emphasise that small, diversified farms are more productive than large monocultures (Barrett et al., 2009; Horlings and Marsden, 2011). To increase the agroecological capacity through a better integration of multiple crop types and varieties in smallholder farming systems is, therefore, a key strategy to fight the world's food security and protect environmental resources. Grain legumes are valuable components in smallholder farming systems of semi-arid areas in Eastern Kenya as they contribute to food and nutrition security and help to manage and restore soil fertility. Increased climate variability however puts additional pressure on these vulnerable systems. Nevertheless, legumes have a great agro-morphological diversity, including varying drought and heat response and adaption mechanisms. In particular, short-season varieties offer new options for farming with increased rainfall variability and restricted growing periods as their adaption strategy of completing the life cycle before the onset of terminal drought seems to be advantageous for cropping with frequent dry spells in semi-arid areas (Loss and Siddique, 1994). The characterization of physiological and growth response to resources and management is, however, a fundamental first step in order to identify niches for new and exciting crop types with multi-purpose benefits for small-scale farming systems. Information on resource capture from field experiments, in particular the utilization of light and water of promising short-season grain legumes in semi-arid environments is, however, largely missing. The first part of this PhD thesis aims, therefore, to analyse the response of three short-season grain legumes to environmental conditions and different management interventions in semi-arid Eastern Kenya (Figure 4).

Two field trials, including a water response and plant density trial, which were conducted over two seasons in semi-arid Eastern Kenya, were designed to quantify the effect of plant population and water availability on crop growth and development to evaluate resource use and use-efficiency with special focus on RUE and WUE. Of particular focus in this thesis are the short-season varieties of two major grain legumes; common bean (*Phaseolus vulgaris* L.) and cowpea (*Vigna unguiculata* (L.) Walp.), which are widely utilized in Eastern Kenya. In addition, lablab (*Lablab purpureus* (L.) Sweet) was selected because of its potential adaption to the region and its local farming systems (Maass et al., 2010). In addition to the field experiments in semi-arid Eastern Kenya, the photoperiod sensitivity of promising short-season lablab accessions was evaluated in an exemplary analysis of combined field and controlled environment data. An improved physiological understanding of the photoperiod response can contribute to better estimate phenological events, such as flowering and maturity with the aim to assess the potential adaption of early-flowering lablab accessions to (sub)-tropical environments as a climate smart farming practice.

In order to explore the potential of certain crops and cropping strategies in diverse and dynamic smallholder farming systems under varying environmental conditions the development and application of crop growth simulation models has been proved to be an excellent tool (Whitbread et al. 2010). Combining field/crop simulation and farm level analysis is necessary to better understand the complexity of genotyp x environment interactions. One of the most applicable models to better understand the complexity of plant growth in response to the environment has been the Agricultural Production System sIMulator (APSIM) framework (Holzworth et al., 2014; Keating et al., 2003). Roberstson et al. (2002) defined and estimated key physiological parameters necessary for modelling legumes growth and development.

Further, the conception of modules to simulate growth and development of further grain and forage legumes such as cowpea (Adiku et al., 1993), soybean (Robertson and Carberry, 1998), pigeonpea (Robertson et al., 2001), mungbean (Robertson et al., 2002) and fababean (Turpin et al., 2002; Turpin et al., 2003), and improvements to the overall module design made by Robertson et al. (2002) the model capability for the simulation of legume production and productivity was enhanced. Despite these efforts in model enhancement, there is very limited published research on the growth and development of short-season legumes, in particular for semi-arid environments. Model validation and testing has focused mainly on Australian production systems and the vegetative or forage types of cowpea and lablab.

The second part of the PhD thesis, therefore, focuses on the estimation of key physiological parameters necessary to parameterize and validate the crop growth model APSIM for the short-season legumes (Figure 4). Further, the objectives were to collect soil and weather information for semi-arid Eastern Kenya to be used in the simulations. If calibrated well, crop growth models can function as powerful tools to explore the potential impact of internal and external factors, including management strategies or the evaluation of climate change effects on growth and development of short-season grain and multi-purpose legumes (Carberry et al., 2002; Cooper et al., 2008; Tittonell and Giller, 2013). The ex-ante assessment through simulation models can help to better identify entry points for short-season grain legumes in existing farming systems of semi-arid Eastern Kenya. Consequently, the last part of the PhD thesis aims first to upscale results from field experiments and characterize possible responses of the short-season grain legumes to different management interventions and environmental conditions, including climate change (temperature and water stress) to estimate their agricultural production potential through multi-site simulations (Figure 4). Finally, the objective of the PhD thesis was to use experimental results together with the model outputs to better design strategies for climate smart agriculture in smallholder farming systems of Eastern Kenya to identify intervention opportunities and pathways towards the sustainable intensification of smallholder systems in sub-Saharan Africa and, thereby, increase food and nutrition security by minimizing the vulnerability to climate variability and change.

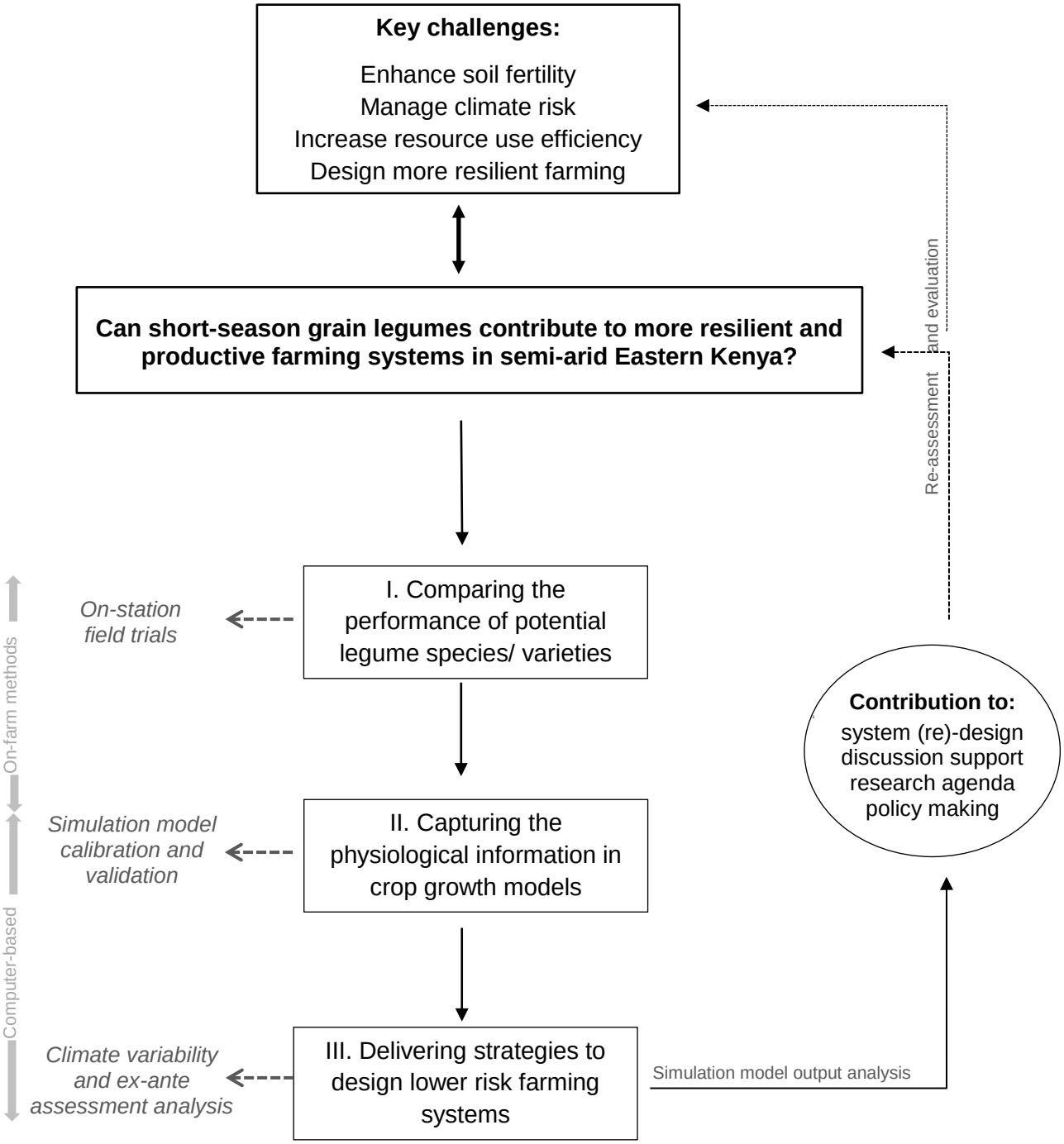

Figure 4: Conceptual framework of the PhD thesis including presentation of the research needs, major tasks and objectives and their trade-offs.

Research objectives

Within the context of the identified research needs, this PhD thesis has the following specific objectives:

1. Enhance the physiological understanding of the potential adaption of early-flowering lablab accessions to (sub)-tropical environments as a climate smart farming practice.
   - Examine the photothermal response of early-flowering lablab genotypes through a combination of field and growth chamber experiments.

2. Evaluate the production potential as well as resource use and use efficiency of short-season grain legumes in semi-arid environments.
   - Assess the RUE and WUE of the short-season grain legumes.
   - Compare the response of short-season grain legumes (common bean, cowpea and lablab) to environmental and management effects.

3. Parameterize and validate APSIM to better simulate growth and development of short-season-grain legumes in semi-arid areas.
   - Identify and quantify essential cultivar-specific parameters to better calibrate APSIM.
   - Validate the crop growth model output (APSIM) to simulate soil water dynamics, biomass accumulation and yield development.
   - Conduct a sensitivity analysis with focus on the species-specific parameters: extinction coefficient (k), radiation use efficiency (RUE) and transpiration efficiency (TE) to evaluate their impact on the model efficiency.

4. Identify possible entry points for short-season grain legumes in resource-constrained smallholder farming systems of semi-arid Eastern Kenya.
   - Characterize climate variability and agro-climatic changes and associated risks for rainfed crop production systems in semi-arid Eastern Kenya.
   - Evaluate the yield potential of short-season grain legumes with varying in-crop rainfall and under different management practices.

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I. Considering effects of temperature and photoperiod on growth and development of *Lablab purpureus* (L.) Sweet in the search of short-season accessions for smallholder farming systems

Introduction

Legumes have proved to be a promising option in small-scale farming systems of sub-Saharan Africa by combining benefits for the farmer, soil and environment. The protein rich grains for example, are an important component in the diet of the mainly subsistence small scale farmers. Furthermore, the ability to fix atmospheric nitrogen is a valued feature for soil improvement and with potential for sustainable intensification of agricultural systems (Vadez et al., 2012). *Lablab purpureus* (L.) Sweet is one of the most diverse domesticated legumes and offers many opportunities to improve food and forage production in semi-arid areas. Besides being better adapted to drought than cowpeas (*Vigna unguiculata* (L.) Walp.) and common beans (*Phaseolus vulgaris* L.), which are widely cultivated in semi-arid areas of the tropics (Hendricksen and Minson, 1985; Maundu et al., 1999), lablab is highly valued because of its multi-purpose uses that include protein rich grains, healthy vegetable leaf and pod products, high quality forage and green manure. The high agro-morphological and physiological diversity of lablab, in particular the short-season types, offer additional options for coping with frequent droughts and reductions in rainfall and rainfall reliability, sustaining soil fertility and stabilizing on-farm production (Maass et al, 2010). However, to increase the potential adoption by farmers and improve agricultural extension and advisory services in semi-arid areas, the phenological responses of promising short-season lablab types need to be better understood.

Matching crop phenology to environmental and climatic conditions is a key concept to be optimized for efficient resource use in (sub)-tropical farming systems (Imaizumi and Kay, 2006; Lawn and James, 2011). In particular, triggering the switch from vegetative to reproductive growth is critically important, since the timing of the transition to flowering and the environmental conditions experienced during this growth phase directly influence yield (Zhang et al., 2000; Putterill et al., 2004). Consequently, physiological research is considered to be a fundamental part of crop selection and breeding programs and can be exploited in cropping system improvement (James and Lawn, 2011). Finally, understanding and quantifying the effects and interactions of photoperiod and temperature on flowering control directly helps to predict and model the time of flowering and maturity under different environmental conditions (Zhang et al., 2000).

In summary, photoperiod is considered to be one of the most significant environmental factors influencing flowering time in legumes and the variation in photoperiod sensitivity among and within legume species is high (Nelson et al., 2010; Roberts and Summerfield, 1987). Three main measures have been developed to describe photoperiod sensitivity. First, the optimum photoperiod where flowering is observed soonest; secondly, the critical photoperiod – the daylength above or below which flowering is delayed (quantitative response) or inhibited (qualitative response); and thirdly, the photoperiod sensitivity expressed as the delay of flowering per unit change in photoperiod. Most of

the legumes from temperate regions are usually quantitative long-day plants (LDP), whereas legumes originating from the tropics are quantitative short-day plants (SDP). However, photo-insensitive or day-neutral plants (DNP) exist within all legume species (Nelson et al., 2010; Roberts and Summerfield, 1987). In plant science, photoperiod sensitivity is usually analyzed as photothermal response, where both photoperiod and temperate effects are considered simultaneously. Quantitative models to predict flowering time are simplified additive linear models with temperature and photoperiod as possible predictors and flowering time as response variable (Keatinge et al., 1998; Summerfield et al., 1991).

Extensive research on photoperiod response of soybean, in particular, has been undertaken because of its economic importance. The findings from Zhang et al. (2000) show that the period from emergence to flowering in soybean decreases dramatically when daylength is reduced during late growing season. Further, the authors demonstrate that the degree of reduction in flowering time with photoperiod change, varies among varieties. The authors show that flowering time in late-maturing varieties is stronger controlled by photoperiod than in early-maturing types. For some early-maturing varieties, photoperiod sensitivity could not be detected clearly in field experiments (Zhang et al., 2000). In growth chamber experiments, the authors demonstrate that long-day photoperiods delay (photoperiod ≥ 14 h) or even inhibit (photoperiod ≥ 16 h) flowering in soybean. However, the critical daylength increases as inverse functions of both increasing photoperiod and decreasing temperature and, consequently, the critical daylength becomes longer with higher mean temperatures (Hadley et al., 1984). Similar observations are made for cowpea (Vigna unguiculata (L.) Walp.) (Hadley et al., 1983). Ellis et al. (1998) studied photoperiod and temperature effects on pigeonpea (Cajanus cajan (L.) Millsp.) in Kenya and the authors observed a delay in the progress towards flowering under long-day conditions as well. These researchers further demonstrated that supra-optimal temperature conditions during the photosensitive floral initiation prolonged the vegetative phase of pigeonpea even under short-day conditions (Ellis et al., 1998; Omanga et al., 1995). For chickpea (Cicer arietinum L.), Roberts et al. (1985) made different observations. The authors determined that time to flowering decreases under long day conditions of 15 h in comparison to 12 h photoperiod. However, from the genotypes included in the analysis, early-maturing ones were less sensitive to photoperiod than late-maturing chickpea varieties. Chickpea is, therefore, assigned to the long-day grain legumes, with a linear function of the mean temperature describing the progress towards flowering (Roberts et al., 1985; Summerfield et al., 1987).

Consequently, many legumes including lablab, are physiologically plastic with both daylength and temperature influencing their growth habit (Kim and Okubo, 1995). Within the lablab landraces, short-day and long-day photoperiod types exist (Kim et al., 1992). Kim and Okubo (1995) also reported for a lablab dwarf variety from India that photoperiod and temperature control the shift from indeterminate to determinate growth; the critical daylength shortens as temperature rises. They concluded that 13 h is the critical daylength at 25 °C, while at 30 °C, a daylength between 10 and 11 h is required for determinate growth. This agrees with the findings of Keatinge et al. (1998) who concluded that time to flowering in lablab (forage type from Honduras) would become excessively long at higher latitudes and greater photoperiod fluctuations and elevations with lower potential of reproduction success.

In commercial production systems, where photoperiod sensitivity can be an undesirable trait, Maass et al. (2010) reported that photoperiod-insensitive lines have been bred and released as year-round cultivars in India and Bangladesh.

The objective of our study was to examine the photothermal response of early-flowering lablab genotypes selected by Whitbread et al. (2011) using a combination of field and growth chamber experimentation to impose varying daylength and temperature regimes. This enhanced physiological understanding is important for identifying the potential adaption of early-flowering lablab accessions to (sub)-tropical environments as a climate smart farming practice

Material and methods

Three datasets were used to investigate the response of daylength and temperature on flowering time of short-season lablab types. The first one (field trial 1) derived from data reported in Whitbread et al. (2011). The dataset was reworked and used to compare thermal time to flowering of lablab accessions tested at three locations in Limpopo province of South Africa: Tompi Seleka (24°47´S, 29°27´E), Venda (22°58´S; 30°26´E) and Dalmada (23°87´S, 29°53´E) planted on different dates (10/02/2002, 10/12/2002, 13/02/2006, respectively). The second dataset (Field trial 2) was from a planting date experiment undertaken at Venda in 2012/2013 using 10 of the lablab accessions identified by Whitbread et al. (2011) as short-season grain types. The third dataset generated on growth chamber studies undertaken at Georg-August University of Göttingen, Germany, where 7 accessions were grown in controlled conditions with various temperature and daylength regimes.

Germplasm

The original germplasm was obtained from the Australian Tropical Forages Genetic Resources Centre (ATFGRC) in Biloela, Australia (http://www.daff.qld.gov.au/services/plant-industries-services/australian-tropical-crops-and-forages-collection). Based on the findings of Whitbread et al. (2011), 9 consistently early-flowering lablab accessions were selected as well as the cultivars ‘Highworth’ (CPI 30212) and ‘Rongai’ (CPI 17883) serving as controls, to further quantify photoperiod sensitivity. Origin, morphological and agronomic characteristics of the selected germplasm is summarized according Maass et al. (2005) and Whitbread et al. (2011) in Table 1.

Table 1: Origin, morphological and agronomic characteristics of 9 lablab accessions and 2 cultivars included in photoperiod analysis study. (Adapted from Pengelly and Maass, 2001; Whitbread et al., 2011)

Accession ID	Origin	Flower color	Seed color	Growth type	Flowering (DAP)	Maturity (DAP)	Leaf DM (kg ha^{-1})	Grain yield (kg ha^{-1})	Number of pods plant^{-1}
CPI 52513[a,b,c]	Zambia	white	greenish	spreading	52-73	91-99	339	227-1400	29.2
CPI 52533 [a,b]	unknown	white	white	spreading	62-67	99	655	348-466	12.5
CPI 52535 [a,c]	India	white	tan	heavily spreading	65-66	100	765	52-360	8.9
CPI 52552 [a,b,c]	unknown	white	white	spreading	60-70	88-99	709	576-1100	18.6
CPI 52554 [a,b,c]	India	white	greenish	bushy spreading	66-73	90-105	1604	382-1900	15.1
CPI 60795 [a,b,c]	unknown	purple	brown	slightly spreading	59-65	75-99	1647	571-731	24.6
CPI 81364 [a,b,c]	USA	white	brown	bushy	59-61	74-102	2144	100-1133	6.6
CQ 3620 [a,b]	unknown	white	white	spreading	63-68	84-99	1855	574-1233	16.8
Q 6880B [a,b,c]	Brazil	purple	black	bushy	43-65	65-102	588	532-933	12.9
Highworth [b,c] (CPI 30212)	India	purple	black	bushy	50-70	110-160	2460	900-1600	n.a.
Rongai [a,b] (CPI 17883)	Kenya	white	dark brown	spreading	159	197	n.a.	7.4	n.a.

[a] accession included in evaluation trial from Whitbread et al. (2011);
[b] accession included in the sowing date trial;
[c] accession included in the growth chamber experiment;
CPI, Commonwealth (of Australia) Plant Introduction;
CQ, Commonwealth Scientific and Industrial Research Organisation (CSIRO) Queensland number;
Q, Queensland number;
DAP, days after planting;
DM, dry matter;
n.a., not available.

Field experimentation

Photoperiod sensitivity was not considered in Whitbread et al. (2011). To investigate this aspect, data were analyzed for the effect of planting time on flowering in combination with the daily maximum and minimum temperature observations collected from the field sites described in that study (Dalmada, Tompi Seleka and Venda). Site and crop management details are summarized in Table 2.

Table 2: Site information and crop management details for an evaluation trial of lablab accessions in Limpopo Province of South Africa.

Location	Latitude	Longitude	Elevation (m asl)	Soil classification	Soil fertility status	Plant density (plants ha^{-1})	In-season rain (mm)	Irrigation (mm)
Dalmada	-23.87540	29.54313	1334	clay loam	neutral pH, adequate levels of P and K	49284	297	178
Tompi Seleka	-24.79330	29.45270	860	shallow, well-drained sandy loam	neutral pH, adequate levels of P and K	3300	131	300
Venda	-22.97781	30.44016	590	deep, well-drained clay	neutral to slightly acid pH, adquate K, low P	41625	539	0

A sowing date trial was conducted during the 2012/2013 growing season at University of Venda experimental farm, about 2 km west from Thohoyandou town in Vhembe district- this is close to the Venda site described in field trial 1. The area receives about 781 mm annual rainfall and it is highly seasonal, with 85 % occurring between October and March (climatic summer) predominantly falling during February and March (Figure 1). Irrigation was not applied, except during to first week to secure uniform germaniation.

The trial was located on a deep well-drained clay, Hutton form (Soil Classification Working Group 1991), Ferrasol according to the classification of the Food and Agriculture Organization (FAO) belonging to Land Type Ab179 (Mzezewa and van Rensburg, 2011) with soil pH neutral to slightly acid, adequate K and very low plant-available P (Mabapa et al., 2010).

Daily and average daylength during the sowing date experiments for Venda were calculated based on geographic coordinates using R package RAtmosphere (Figure 2) (Teets, 2003).

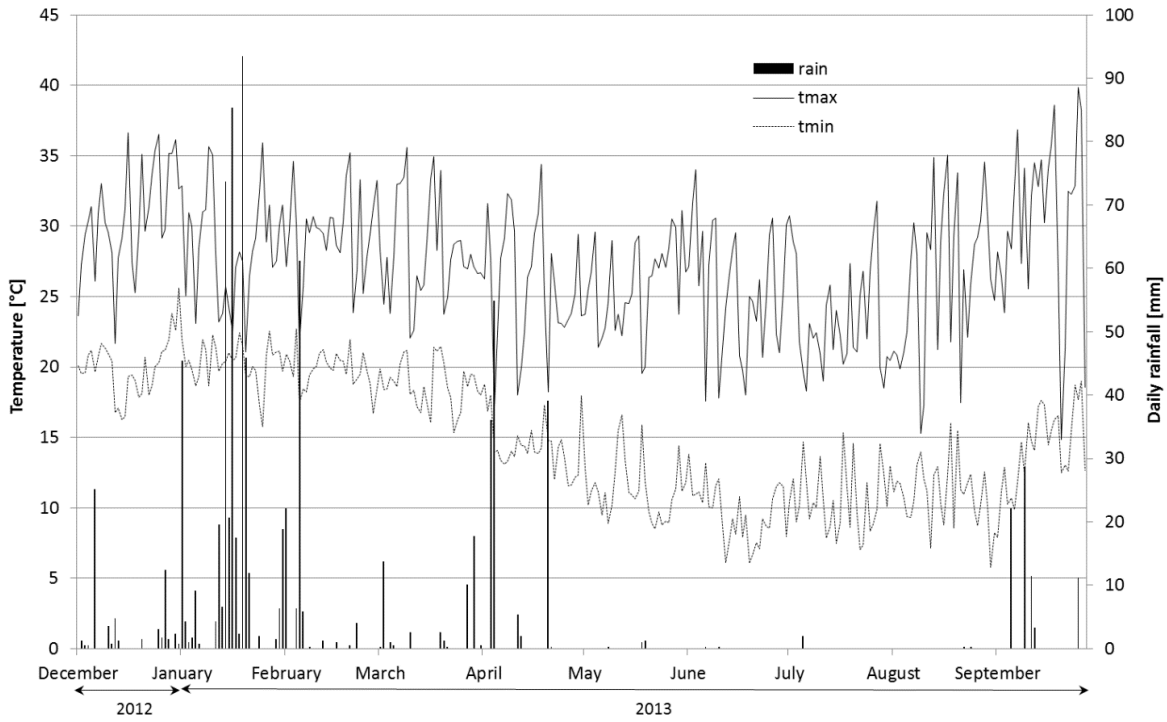


Figure 1: Daily minimum and maximum temperatures and rainfall at University of Venda, Thohoyandou, Limpopo Province, South Africa from December 2012 until September 2013.

The sowing date field trial was implemented as a randomized complete block design with sowing date as main plots and the different lablab accessions as sub plots, replicated three times. Sowing was done at 1-month intervals from 11/12/2012 and 4 subsequent sowings on 11/01/2013, 11/02/2013, 11/03/2013, and 13/04/2013, resulting in daylength decreasing from 13.56 h at the first sowing to 11.67 h by the final date of sowing (Figure 2). The temperatures ranged from high mean daily temperatures at the December, January and February sowing date (24.3, 24.7 and 25.4 °C respectively) with mean maximum temperatures of above 28 °C to comparatively low mean temperatures of 20.5 and 18.4 °C, respectively, at the March and April sowings with very low mean minimum temperatures of below 15 °C from April onwards (Figure 2). Each plot was 10 x 2 m and consisted of 10 rows with an inter-row spacing of 1 m and 20 cm between plants (50.000 plants ha^{-1}). All seeds were inoculated with *Bradyrhizobium* strain CB756 (XS21) prior to seeding. Superphosphate was applied during sowing at a rate equivalent to 20 kg P ha^{-1}.

The seeds were sown by hand at 4-6 cm depth and thinned two weeks after emergence to the desired spacing. Weeds were controlled manually and pests with Chlorpyriphos as required. Additional irrigation was not applied. The data collected included time to 50 % flowering (50 % of plants flowering) in days after planting (DAP). Additional to agronomic data, daily rainfall, as well as minimum and maximum temperatures were recorded throughout the experiment on a daily basis.

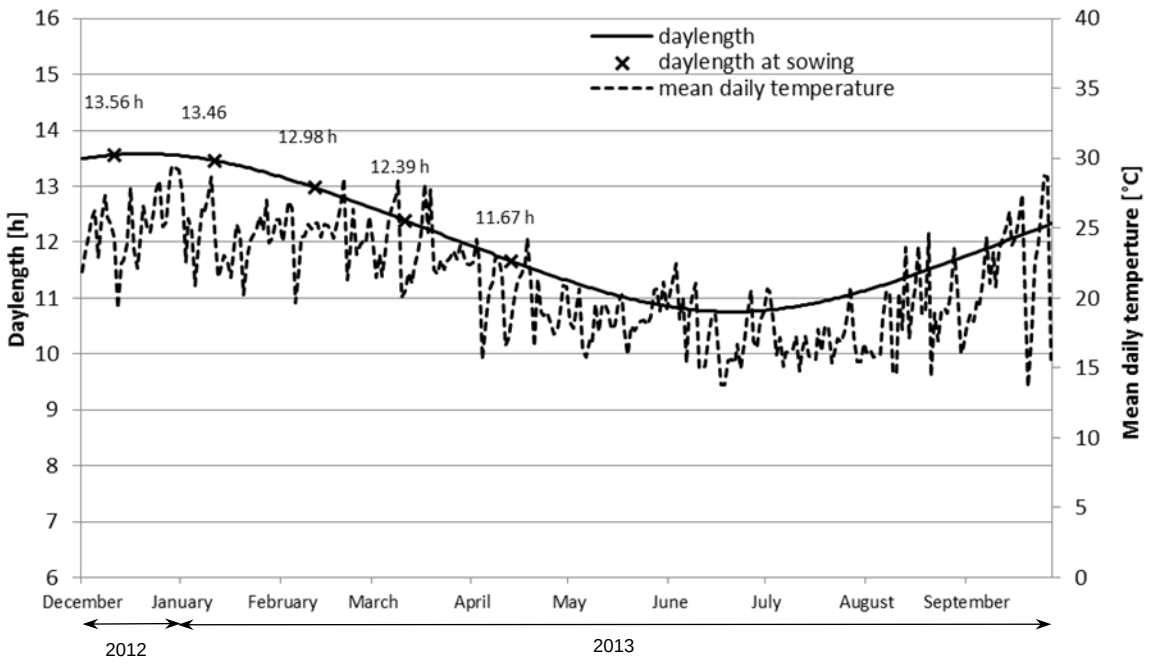


Figure 2: Daylength and mean daily temperature at University of Venda, Thohoyandou; Limpopo Province, South Africa throughout the year. With indications for daylength at different sowing dates included in the sowing date trial.

Growth chamber experiments

Based on the availability of seed, six of the nine lablab accessions included in the sowing date trial plus accession CPI 52535 from the evaluation experiment by Whitbread et al. (2011) were chosen for further evaluation under controlled conditions in a growth chamber. The selected accessions showed consistently early-flowering and high-yielding characteristics even in water-limited environments (Pengelly and Maass, 2001; Whitbread et al., 2011). These accessions were grown at four daylength regimes (10, 12, 14, 16 h of full light intensity) at a constant day/night temperature of 28 °C and relative humidity of 75 %, replicated 3 times. The same experiment was repeated using a constant day/night temperature of 20 °C. Average light intensity in the growth chambers was set to 450 µmol m^{-2} s^{-1}. Three seeds were sown per pot (height: 13 cm, diameter: 16.5 cm) and thinned to 2 plants per pot seven days after emergence. The potting mix was a 6:2:2 ratio of humus, sand and loam (vol./vol.). Pots were transferred to the growth chambers seven days after planting and placed in separate growth chambers (2 growth chambers in 2 floors with individual light adjustment possibilities; length: 2.15 m, width: 0.7 m, height: 0.6 m) for each daylength regime, following a completely randomized design and rotated once a week. Watering was realized three times a week to avoid water shortage.

From one month after planting a complete fertilizer solution (Hakaphos® rot) was applied at ten-day intervals. The parameters measured included time to flowering of each individual plant in days after planting (DAP). Flowering time was recorded when 50 % of the buds on one plant fully flowered.

Data analysis

For the field trials, site-specific daylength was computed using R package ´RAtmosphere` (Teets, 2003). Mean photoperiod as well as temperatures were calculated for the phenological phase from planting to flowering for each site, sowing date and accession individually for the field trial datasets. To evaluate photoperiod sensitivity, time to 50% flowering was determined with respect to DAP and thermal time (T_t, °Cd). Thermal time, expressed in degree days (°Cd), was computed using the algorithms in CERES-Maize, which divides each day into eight 3-h time periods on the basis of daily inputs of maximum and minimum temperatures (Jones et al., 1986). Base, optimal and maximal temperatures (T_b, $T_{optimal}$, T_{max}, °C) were assumed to be 10, 30 and 40 °C respectively, as suggested by Hill et al. (2006).

Further, the development towards flowering was expressed as development rate - the reciprocal of the duration from sowing to flowering ($(1/f) = D$, d^{-1}). The thermal and photothermal response of flowering was described using the triple–plane rate model (Summerfield et al., 1991).

First, for photoperiod-insensitive plants the development rate can be expressed as a function of mean daily temperature (T, °C) only from sowing to flowering as:

$$D = a + bT. \quad (1)$$

The same formula can be applied for daylength shorter than the critical photoperiod (P_c) in photoperiod-sensitive short-day plants (SDP) (or longer than the critical photoperiod in photoperiod-sensitive long-day plants, LDP).
Secondly, after adding mean daily photoperiod (P, h d^{-1}) as variable to the additive linear response model, the development rate can be described as:

$$D = a´ + b´T + c´P \quad (2)$$

for daylength between the critical photoperiod (P_c) and ceiling photoperiod (P_{ce}), where $a´, b´$ and $c´$ are genotypic coefficients (Iannucci et al., 2008; Summerfield et al., 1991).
Thirdly, the maximum delay in flowering is reached when the daylength exceeds the ceiling photoperiod (P_{ce}) in SDP (for daylength below P_{ce} in LDPs) and the development can be expressed as:

$$D = d´ \quad (3)$$

independent of variations in P or T.
From the photothermal model, the critical photoperiod (P_c) can be predicted for photo-sensitive plants:

$$P_c = [a - a´ + T(b - b´)]/c´ \quad (4)$$

(Keatinge et al., 1998; Summerfield et al., 1991).

Additionally, a mixed model was used to further describe photoperiod response of the tested lablab accessions. In a first step, flowering response was scored as a simple yes/no event for the different temperature and daylength regimes. Secondly, the critical photoperiod (P_c) above which flowering was accelerated in SDP was quantified by piecewise regression analysis for photoperiod-sensitive accessions using the R package ´segmented` (Muggeo, 2003, 2008). All statistical analyses were computed using R 2.15.1 (R 2008).

Results

Field trial 1

In contrast to the well-studied forage-type lablab cv. Rongai, the lablab accessions included in this study are short-season with flowering times of 70 days or less. Time to flowering remained relatively stable across a range of sites and planting dates under field conditions in South Africa and the variation in flowering time in DAP or thermal time were limited (Table 3). Whereas average temperatures from planting to flowering were comparatively similar at all three sites ranging from 21 to 24 °C, mean daylength was about 13.50 h at Dalmada during the period from planting to flowering (December to March) and about 12.20 h at Venda and Tompi Seleka from February to May. In Dalmada, accession CPI 52513 flowered earliest at 52 DAP, while in Venda and Tompi Selaka, Q 6880B flowered earliest at 45 and 43 DAP, respectively (<605 °Cd). Cultivar Highworth flowered consistently early (63 to 68 DAP/800 – 862 °Cd) compared to cv. Rongai an indeterminate cultivar (157 DAP/1728 °Cd).

Field experiment – sowing date trial

Variation in flowering time of the studied short-season accessions appears great if expressed in DAP, but relatively constant if expressed in thermal time units. This is illustrated by comparing DAP (Figure 3a) and thermal times (T_t) (Figure 3b) to flowering for the ten different lablab accessions at five different sowing dates. Therefore variation in flowering time was considerable high, when expressed in DAP, and ranged from 50 to above 100 DAP for the majority of the tested accessions and from 50 to 80 DAP for sowing dates after December (CPI 52513, CPI 525233, CPI 52552, CPI 52554, CPI 60795, CPI 81364 and CQ 3620) (Figure 3a). However, if expressed in °Cd the sowing dates after December had little impact on time to flowering, which was consistently at around 800 °Cd for the same accessions (Figure 3b). For the December sowing date, though, flowering was delayed. The extent of delay in flowering time was relatively low for CPI 52513, CPI 52533 and CPI 52554, with T_t requirements of about 1000 °Cd in the December sowing. However, for accessions CPI 81364 and CQ 3620 the thermal time period increased to about 1100 °Cd. The greatest increase was observed for CPI 52552 where thermal time to flowering was greater than 1200 °Cd in the December sowing. The opposite was true for accession Q 6880B where time to flowering was observed later after sowing in April (1000 °Cd) than after sowing in December (800 °Cd). Only for accession CPI 60795, thermal time to flowering remained constant across all planting dates.

Table 3: Summary of flowering time data in days after planting (DAP) and thermal time (°Cd) for eleven different lablab accessions from three sites and planting dates in Limpopo Province of South Africa.

Location	Planting date, daylength at sowing (h)	Lablab accession	Flowering time (DAP)	Thermal time to 50% flowering (°Cd)	Mean daylength from planting to flowering (h)	Mean daily temperature from planting to floweirng (°C)
Dalmada	10/12/2002	CPI 52513	52	661.55	13.52	22.48
	13.62	CPI 52533	62	788.15	13.46	22.51
		CPI 52535	65	824.95	13.43	22.50
		CPI 52552	60	765.00	13.47	22.54
		CPI 52554	67	849.15	13.42	22.49
		CPI 60795	61	776.65	13.46	22.53
		CPI 81364	61	776.65	13.46	22.53
		CQ 3620	63	800.25	13.45	22.50
		Q 6880B	65	824.95	13.43	22.50
		Highworth	63	800.25	13.45	22.50
		Rongai	157	1727.82	12.56	20.93
Tompi Seleka	13/02/2008	CPI 52513	73	896.59	12.15	22.51
	13.00	CPI 52533	n.a.	n.a.	n.a.	n.a.
		CPI 52535	n.a.	n.a.	n.a.	n.a.
		CPI 52552	70	873.58	12.19	22.72
		CPI 52554	73	896.59	12.15	22.51
		CPI 60795	59	774.02	12.32	23.41
		CPI 81364	59	774.02	12.32	23.41
		CQ 3620	68	862.26	12.21	22.95
		Q 6880B	43	587.18	12.51	23.99
		Highworth	68	862.26	12.21	22.95
		Rongai	n.a.	n.a.	n.a.	n.a.
Venda	13/02/2006	CPI 52513	66	840.48	12.23	22.64
	12.94	CPI 52533	67	850.30	12.22	22.60
		CPI 52535	66	840.48	12.23	22.64
		CPI 52552	64	821.68	12.25	22.74
		CPI 52554	66	840.48	12.23	22.64
		CPI 60795	65	829.73	12.24	22.67
		CPI 81364	50	663.87	12.41	23.13
		CQ 3620	65	829.73	12.24	22.67
		Q 6880B	45	604.21	12.46	23.26
		Highworth	65	829.73	12.24	22.67
		Rongai	n.a.	n.a.	n.a.	n.a.

n.a., not available. (Source: recalculated from raw data used in Whitbread et al., 2011).

Flowering of cultivars Highworth and Rongai, was significantly delayed in the December and January sowings when compared to later dates. The thermal time requirement to flowering was almost doubled with T_t > 1500 °Cd for cv. Highworth and T_t of almost 1800 °Cd for cv. Rongai in the December sowing. Since daylength decreased from the December (13.56 h) to the April (11.67 h) sowing date, cvs. Highworth and Rongai showed a strongly quantitative short-day plant response and are, therefore, considered photoperiod-sensitive. In comparison to cvv. Highworth and Rongai, the response of accessions CPI 52513, CPI 525233, CPI 52552, CPI 52554, CPI 81364 and CQ 3620 to increasing daylength can be regarded as weak. From the sowing date field experiment, only CPI 60795 can be categorized as consistently early-flowering and independent of photoperiod. Interpretation of photoperiod sensitivity is, however, limited analyzed irrespective of temperature (in DAP) as illustrated in Figure 3. Variation in flowering time of the studied short-season accessions appears great if expressed in DAP, but relatively constant if expressed in thermal time units for sowing dates from January till April.

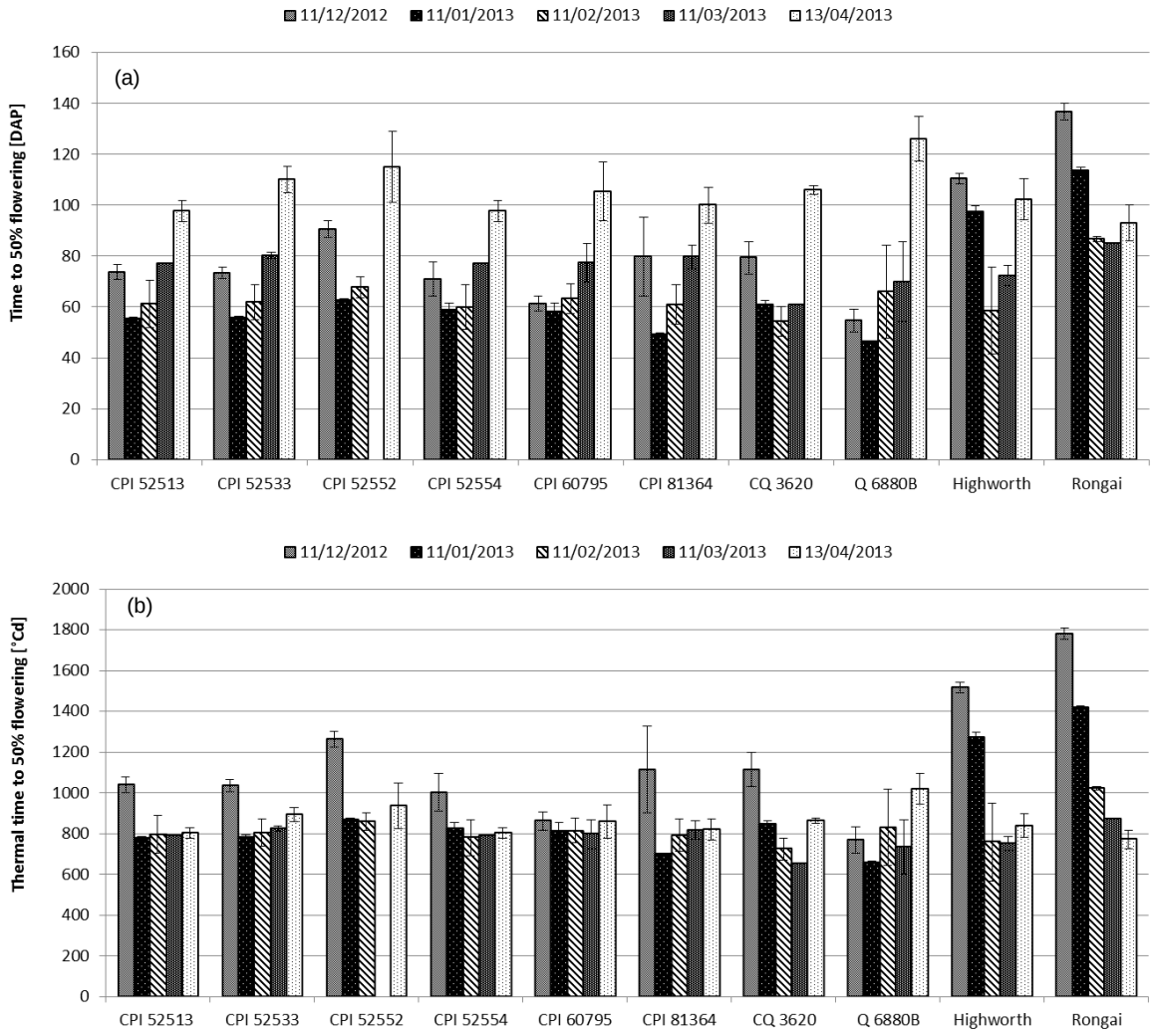


Figure 3: Days after planting (a) and thermal time (b) to 50% flowering [°Cd] for monthly sowing dates and different lablab accessions and cultivars evaluated at University of Venda, Thohoyandou; Limpopo Province, South Africa. (Crop failure for accession CPI 52552 at the March sowing date).

Growth chamber experiment

In general, lower temperature resulted in time to flowering being longer. At 20 °C, all accessions flowered within 110 DAP (Figure 4 (a)). At 28 °C, however, only accessions CPI 81364 and Q 6880B flowered at all daylengths from 10 to 16 h (Figure 4 (b)). Accessions CPI 52554 and CPI 60795 flowered only at daylength regimes from 10 to 14 h at 28 °C, while CPI 52513 and CPI 52535 only at daylength of 10 and 12 h. At 20 °C mean temperature, an increase of time to flowering in DAP was observed with increased daylength for all accessions except cv. Highworth from about 60 to 80 days at a daylength of 10 h up to 85 to 110 days at a daylength of 16 h. Cultivar Highworth only flowered under short-day conditions of 10 h at 28 °C and at photoperiods of 10 and 12 h at 20 °C.

Within accessions variation in flowering response to daylength was rather low for the majority of the tested accessions. And on average flowering was delayed by 4 days with a 2 h increase of in daylength. Only accession Q 6880B was highly responsive to changes in daylength at temperatures of 20 °C, and flowering was accelerated significantly with decreasing daylength. Under temperatures of 28 °C and all daylengths, however, Q 6880B flowered within a very short time of about 50 day.

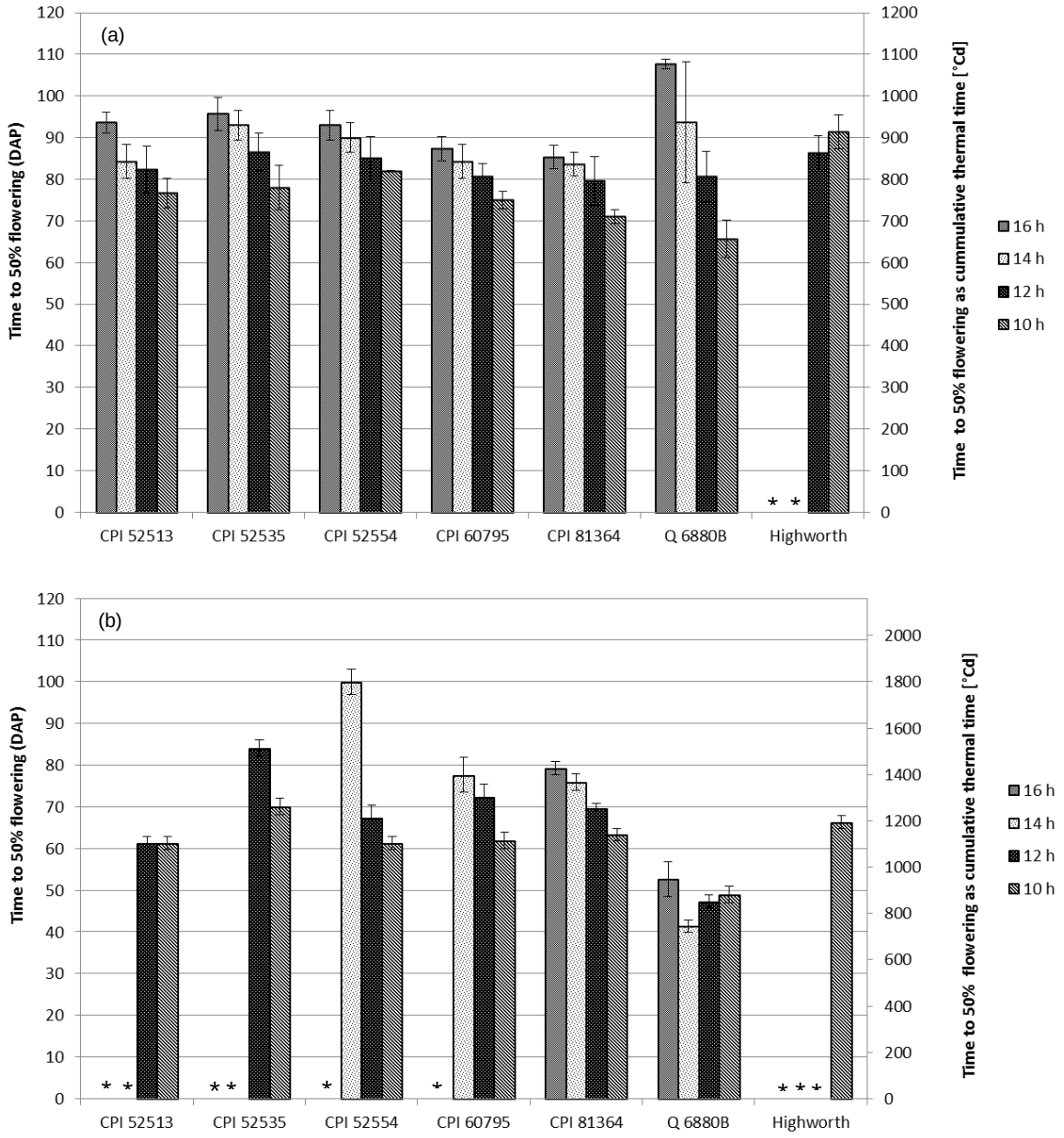


Figure 4: Time to 50% flowering in days after planting (DAP) and thermal time (°Cd) for different daylengths and lablab accessions under controlled environment in a growth chamber; (a) – at 20 °C and (b) – at 28 °C.
* indeterminate growth up to 110 DAP

Applying the triple-plane-rate model to analyse the photothermal response, temperature alone was not enough to explain phenological development towards flowering. The coefficient of determination was low (R^2 <0.5) for the tested accessions except for CPI 52513 and CPI 60795, with R^2 of 0.86 and 0.81, respectively (expressed by b, Table 4). However, for all accessions, the interval from planting to 50 % flowering, expressed as inverse of the duration, was highly correlated (R^2 ≥0.77) to mean both temperature and mean photoperiod. The effect of photoperiod was significant and negative for all tested accessions (expressed by c', Table 4), meaning that, with increasing daylength, the development rate decreased significantly. Cultivars Highworth and Rongai were excluded from the triple-plane-rate model analysis because of their strongly qualitative photoperiod response in this experiments as it was terminated 110 DAP independent of the flowering success.

Table 4: Estimated relations derived from the triple-plane rate model of flowering response of the rate of progress from sowing to 50 % flowering for different lablab accessions under controlled environment in a growth chamber. Values of constants a, a´, b, b´ and c´ (all x10^{-4}) derived from regressing the rate of progress to flowering ($1/f = D$) against mean air temperature and photoperiod.

Accession	Thermal response			Photo-thermal response				Critical photoperiod
	a	b	R^2	a´	b´	c´	R^2	(P_c, h)
CPI 52513	1.05	5.45***	0.86	71.48	4.60***	-3.39***	0.95	20.53
CPI 52552	71.90	2.11*	0.34	156.70	0.93	-4.71***	0.77	17.75
CPI 52554	58.21	2.82*	0.27	155.60	2.04*	-6.28***	0.82	15.38
CPI 60795	72.12	2.53***	0.44	142.20	1.96***	-4.52***	0.80	15.38
CPI 81364	91.13	1.73**	0.27	151.30	1.73***	-4.62***	0.86	13.02
Q 6880B	111.46	11.56***	0.81	-44.67	11.56***	-5.14*	0.86	n.a.

* P < 0.05; **P < 0.01; ***P < 0.001; a and a´: day^{-1}; b and b´: $°C^{-1}$; c´: h^{-1}; n.a., not availible.

Finally, the use of piecewise regression analysis to estimate the 'changepoint' (P_c) in thermal time as a function of daylength from all three datasets confirmed the results from the triple-plane rate model analysis: except Q 6880B all accessions can be classified as photoperiod-sensitive, but with varying degree. For accession Q 6880B, neither a significant change in thermal time requirement to 50 % flowering nor a significant effect of daylength on flowering time was found. The same was true for accession CPI 60795 under temperatures of <28 °C, whereas with temperatures ≥28 °C, no flowering was determined within 100 DAP at daylength of ≥16 h. For accessions CPI 52513 and CPI 52535, no significant effect of photoperiod on thermal time requirements could be found for mean daily temperatures of ≤24 °C, but under temperatures of 28 °C, no flowering within 110 DAP was observed at 14 and 16 h daylength. Accession CPI 81364 flowered throughout all tested temperature and daylength regimes, but thermal time requirements to 50 % flowering significantly increased from 800 to 1100 °Cd at daylength from ≤14 h onwards. The same was true for accession CPI 52554, whereas indeterminate growth up to 110 DAP was observed at 28 °C (Figure 4). Thermal time requirements to flowering for cv. Highworth showed a high variation from 600 to 1200 °Cd at daylength of ≤14 h, but continuous vegetative growth up to 110 DAP was observed at 14 and 16 h as well as 12, 14 and 16 h at 20 and 28 °C, respectively, under controlled conditions.

Discussion

Lablab purpureus – short season grain types

A major finding of this study, in particular the analysis of the triple-plane rate model, is that the tested short-season lablab accessions are photoperiod-responsive short-day plants and that both, temperature and photoperiod trigger the flowering response. These findings are in agreement with those of Kim and Okubo (1995) and support evidence that the switch from the vegetative to reproductive phase in lablab is strongly determined by the interaction between temperature and photoperiod. Observed flowering times were highly variable in terms of DAP at different temperature regimes (Figure 3a, Figure 4). In particular, data derived from the sowing date field experiment in Venda, South Africa including different photoperiod and temperature conditions, revealed a high variation in observed flowering times in DAP, ranging from about 60 to 120 DAP for the different short-season lablab accessions (Figure 3a). These observations are similar to results from Keatinge et al. (1998), where the flowering time of lablab originating from Honduras ranged from 69 DAP at 26.9 °C and 11.5 h daylength to 172 DAP at 16.9 °C and 14.5 h daylength under controlled conditions. The strong dependency of development time on temperature make the interpretation of flowering time in DAP across a range of sites and sowing dates rather difficult. The presentation of development in thermal time instead makes it easier to compare results of different experiments or studies (Trudgill et al., 2005). Figure 5 summarizes the results from the different data sets included in the analysis (field trial and controlled environment experiment). The cultivars Highworth and Rongai are clearly photoperiod-responsive short-day plants, as their flowering time increases continuously with increasing daylength. Flowering times for these cultivars were below 1000 °Cd under daylength conditions of ≤ 12 h, however, flowering times increased to about 1500 °Cd for Hightworth and 2000 °C for Rongai at daylength of ≥ 13.5 h. Accessions CPI 52513, CPI 52554, CPI 60796 and CPI 81364 instead showed a comparatively weak photoperiod response as flowering was only delayed by 100 to 300 °Cd at daylength above 13.5 h and, in general, much lower in comparison to the cultivars Highworth and Rongai. Only at higher temperatures in the growth chamber experiment flowering was significantly delayed for the accessions CPI 60796 and CPI 81364 or not observed within 110 DAP for the accessions CPI 52513 and CPI 52554 at daylength above 13.5 h. These observations indicate that 28 °C is above the optimal temperature range for most of the short-season lablab accessions included in the growth chamber experiment (CPI 52513, CPI 52535, CPI 52554, CPI 60796, CPI 81364, Highworth), as their development was clearly delayed if measured in °Cd except for accession Q 6880B. Regardless of conditions, accession Q 6880B showed no significantly delayed development, indicating no photoperiod sensitivity even at higher temperatures (Figure 5). Temperatures of about 28 °C should, however, still be within the optimal range, as most of the accessions originate from tropical countries and are successfully cultivated in India with similarly high temperatures (Maass et al., 2005). Nevertheless, the species-specific selection of cardinal temperatures might not be exact enough to quantify the development of lablab accessions from all over the world. But implementing cultivar-specific cardinal temperatures would add to the complexity and increase the difficulty of applying such concepts. At the same time, P_c seemed to be influenced by temperature itself, as no flowering was observed within 110 DAP at higher temperatures of 28 °C in the growth chamber experiment at daylength of ≥14 h for CPI 52513 and CPI 52535, and

daylength of ≥16 h CPI 52554 and CPI 60795 in comparison to 20 °C were all short-season lablab accessions flowered within 110 DAP (Figure 4). This is in agreement with observations of Kim and Okubo (1995), highlighting that the critical daylength is shorter the higher the temperatures are. Therefore, it is not always suitable to define only one value for P_c, as P_c seems to be temperature dependent itself. The results further proved that below the critical daylength (P_c) or as long as photoperiod requirements are met, the development is dominated by temperature only - within the optimal range, reproductive development is accelerated as temperatures increase.

Consequently, the key findings from this study are that the short-season lablab accessions are SDP and that P_c above which flowering is delayed, decreases with increasing temperatures except for Q 6880B, where no influence of temperature on P_c was found. At temperatures above 20 °C flowering was significantly delayed at daylength of 13.5 h and higher for CPI 52513, CPI 52533, CPI 52535, CPI 52552, CPI 52554, CPI 81364 and CQ 3620. This is in accordance with Keatinge et al. (1998), who determine P_c to be 13.9 h for lablab. They further concluded that time to flowering in lablab would become excessively long with lower potential reproduction success at higher latitudes and elevations (Keatinge et al., 1998).Nevertheless, the analysis of the different data sets derived from field and controlled environment experiments showed some inconsistency, which made it difficult to extract clear relations and dependencies in respect to photoperiod sensitivity for all accessions. This is because the development of legumes does not only respond to environmental factors like temperature and photoperiod, but is further strongly influenced by others such as the water availability, for instance (Subbarao et al., 1995). Furthermore, some of the inconsistency within the data, in particular the field observations, can be attributed to the developmental plasticity of short-season lablab accessions. The accelerated development (663.9 °Cd) of accession CPI 81364 at Venda under short-day conditions (12.4 h) and warm temperatures (23.1 °C) in comparison to the comparatively long flowering time (774.0 °C) under almost similar conditions in Tompi Seleka (Table 3) can be ascribed to developmental plasticity. In comparison to the other lablab accessions the determined photoperiod-sensitivity of CPI 81364 was rather weak under controlled conditions (Figure 4). In general, variability in flowering time observed in the field was relatively high as it is usually difficult to control for all environmental factors which influence development under field conditions. Only flowering time of accession CPI 52513 in the evaluation of Whitbread et al. (2011) was contradictory to the observations of the sowing date and growth chamber experiments, where the development was accelerated under longer day conditions (13.5 h) in Dalmada in comparison to the other sites with daylength below 13 h (Table 3). However, in Dalmada the seasonal rainfall was below 300 mm and supplementary irrigation was applied (Whitbread et al., 2011). Therefore, the possible high drought sensitivity of CPI 52513 (Grotelüschen, 2014) and the soil moisture deficit could have caused accelerated development under field conditions in Dalmada. In general, the phenological plasticity of legumes adds to the complexity of interpreting genotype x environmental interactions. High variation in flowering response determined by diverse environmental triggers apart from photoperiod and temperature is a widespread phenomenon in legumes (Subbarao et al., 1995). Nevertheless, the observed flexibility of development is an advantageous feature to better respond to soil moisture availability in semi-arid environments for instance.

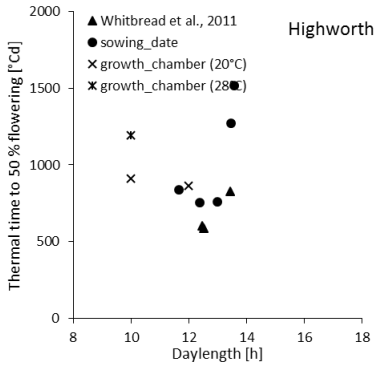
Limitations of the estimation of photoperiod sensitivity

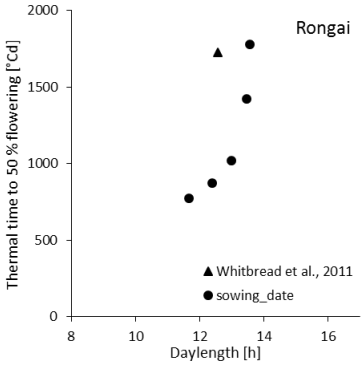
Many photoperiod analyses (e.g., Gaynor et al., 2011; Iannucci et al., 2008; Keatinge et al., 1998; Papastylianou and Bilalis, 2011) use the triple-plane rate model of flowering (Summerfield et al., 1991) to study photoperiod sensitivity of annual crops. However, the model is strictly additive and ignores interaction effects of temperature and photoperiod (Folliard et al., 2004; Wallace and Yan, 1998). Furthermore, the present study highlights some restrictions in applying the simple regression model on data derived from field studies, where mean daily temperatures are correlated to sunshine hours per day, as observed for the study site at the University of Venda, Thohoyandou; Limpopo Province, South Africa (Figure 2). Consequently, the variation in critical daylength together with temperature, as shown by current results, has a hyperbolic characteristic itself, adding to the complexity of quantifying photothermal response (Roberts and Summerfield, 1987; Wallace and Yan, 1998). Because of the correlation of temperature and photoperiod in the data, the observations from the field experiment in South Africa needed to be excluded from the triple-plane rate analysis in this study. Otherwise, development time would have increased (if expressed in DAP) with decreased daylegth and mean daily temperatures would have led to misinterpretation of photoperiodic response (Figure 3a). In this case the analysis of flowering time in thermal time units makes the quantification of the impact of photoperiod clearer (Figure 3b). In terms of thermal time requirement, development is consistent and synchronized for the tested lablab accessions up to a daylength of 13 h. Nevertheless, development, expressed as duration in DAP, can vary highly even under a daylength of 13 h (Figure 3a) as a result of varying temperatures. Recommendations should, therefore, consider the 3-dimensional character of photoperiodic response.

Moreover, daylength is never static in natural environments and directly influences changes in the mean day temperatures over the year. To set suitable photoperiod references for the analysis of field observations is, therefore, complex. Some studies use photoperiod at sowing, others photoperiod at flowering or the mean photoperiod from sowing to flowering. Calculating means might however not be representative, as it is difficult to determine the actual photoperiod that has triggered or inhibited the switch from vegetative to reproductive development. In fact, the changing character of photoperiod within the year or cropping period is neglected in the model by Summerfield et al. (1991). Moreover, the effect of decreasing or increasing daylength itself, or the impact of strictly constant daylength in controlled environment experiments has rarely been studied in annual crops.

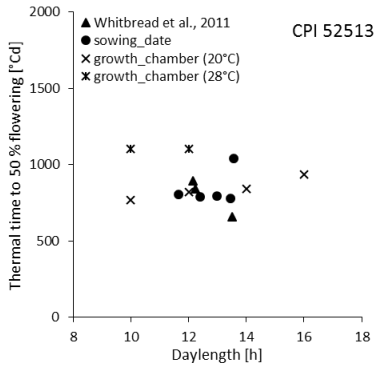
Finally, the linear regression model applied is unable to describe a qualitative photoperiod response and phenomena such as a reversion in the development from vegetative to reproductive back to vegetative (Carberry et al., 2001). Observations of no flowering as recorded at temperatures of 28 °C in the growth chamber experiment (Figure 4b) for instance cannot be appropriately considered in this analysis. This makes the interpretation of the results from the triple-plane rate model (Table 4) even more difficult. On the other hand, many authors (e.g. Iannucci et al., 2008) confirm the usefulness of evaluating photothermal response of flowering time with linear models that permit to estimate base temperatures and thermal time requirements.

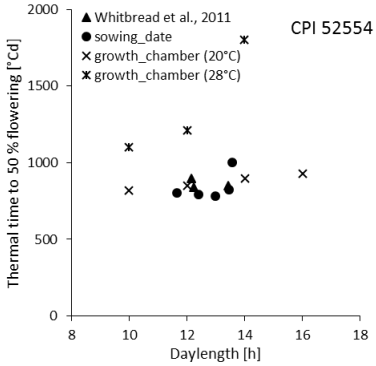
Photoperiod sensitive

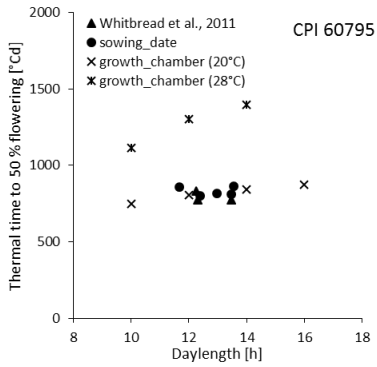


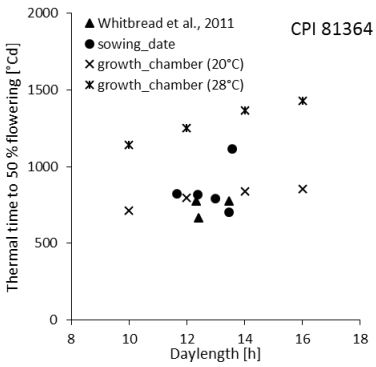


Weak photoperiod sensitive, delayed/no flowering at higher temperatures









Not photoperiod sensitive

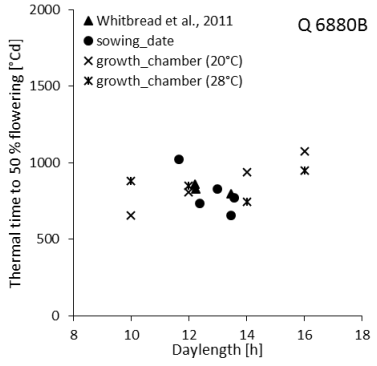


Figure 5: Summary of field trial and controlled environment experiment data representing flowering time in °Cd in response to daylength for lablab accessions grouped according to their photoperiod sensitivity.

These models manage to simplify the complexity of photoperiod response and are, in general, very effective in describing genotype, environment and genotype x environment effects (Lawn and James, 2011). It is of great importance to manage the complexity of genotypic diversity in flowering behavior as it is risky to extrapolate individual photothermal responses and computed coefficients without precaution (Iannucci et al., 2008)

Plasticity in photoperiod response – chance and challenges for agricultural systems

In general, grain legumes have high intraspecific diversity in terms of flowering time, as observed in the studies on lablab accessions and cultivars, which can be exploited for developing plant types that are well adapted to specific environments (Lawn and James, 2011; Nelson et al., 2010). As daylength has an effect on crop phenology and morphology, potential productivity is directly influenced (Craufurd and Wheeler, 2009; Bhattacharya and Vijaylaxmi, 2010). The cultivation of potential short-season lablab accessions under optimal daylength conditions in the tropics and subtropics increases the synchrony of flowering and, consequently, pod setting and maturity. An increased synchrony of flowering and maturity facilitates crop management and harvest, which is of great interest for labor-restricted small-scale farming systems (Bhattacharya and Vijaylaxmi, 2010; Nelson et al., 2010).

Furthermore, shortened growing periods make the studied short-season lablab types interesting for farming in unstable environments, as short-season early-maturing types may be able to escape from external drought at grain filling and shortened growing windows (Blum, 2005, 2009). Therefore, the estimation of flowering time is increasingly important for agronomists and breeders, for whom the right timing of resource use is crucial for production success (Craufurd and Wheeler, 2009; Bhattacharya and Vijaylaxmi, 2010). Flowering within optimal environmental conditions secures production success, making short-season lablab types increasingly interesting for the design of resilient farming systems. The significance of predicted temperature increases in line with climate variation on the phenology of photoperiod-sensitive crops has not yet been fully examined (Craufurd and Wheeler, 2009; Nelson et al., 2010). Present results indicate that higher temperatures can increase the magnitude of photoperiod sensitivity and influence the threshold of the critical photoperiod (Figure 4) (Roberts and Summerfield, 1987; Wallace and Yan, 1998). The predicted temperature increase for potential cropping areas in Sub-Saharan Africa might, therefore, lead to a delay in the development of photosensitive lablab types. This highlights the importance of breeding efforts from India and Bangladesh, for example, that aim to release photo-insensitive short-season lablab genotypes, which increase independence of customary growing periods (Maass et al., 2010). Moreover, the pronounced phenological plasticity of legumes adds to the complexity of determining G x E effects and is complicated to be captured well within crop growth models. However, magnitude of flexibility in growth and development of legumes in response to resource availability holds promising potential for farming with increasing climate uncertainties.

Conclusion

To integrate new germplasm into new environments, quantifying photothermal response information is critical to understand the timing of phenological events, such as flowering and maturity. The analysis proved that both temperature and photoperiod influence the development of the studied legume accessions and cultivars. Photoperiod sensitivity should, therefore, always be interpreted as a photothermal response rather than a strict one in respect to either temperature or photoperiod alone. This study has revealed considerable intraspecific physiological variation in flowering time amongst the lablab accessions and cultivars tested. In comparison to the forage types, cvv. Highworth and Rongai, the remainder can be classified as consistently early-flowering short-day plants (SDP), with a thermal time requirement of about 800 °Cd to flower under daylength conditions of ≤13.5 h and within their optimal temperature regime. The results proved that below the critical daylength (P_c) or as long as photoperiod requirements are met, the development is dominated by temperature only - within the optimal range, reproductive development is accelerated as temperatures increase. The critical photoperiod, P_c above which flowering is delayed, however, decreases with increasing temperatures. Since daylength does not exceed 13 h between latitude 30°N to 30°S covering the semi-arid tropical regions, these lablab accessions can be further evaluated for their adaption to and productivity under farm conditions.

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II. Understanding growth and development of short-season grain legumes for climate smart agriculture in semi-arid Eastern Kenya

Introduction

The agricultural landscape in much of Eastern and Central Africa including Eastern Kenya is dominated by maize production. However, the productivity of the predominantly small-scale farms is poor and grain yields of maize average from 0.3 to 2.2 t ha-1depending on the region (Muhammad et al., 2010). Against this background legume production has been widely promoted to address the challenges of resource-poor farmers in semi-arid areas. Grain legumes in particular offer a great potential to diversify the existing cropping systems and are highly valuable for their multiple benefits. Under subsistence conditions of sub-Saharan Africa, for example, the proportion of legume protein N in the human diet is extraordinarily large compared to the western world (Vance et al., 2000). In addition to the important impact on food and nutrition security in rural areas, legumes are key components in agricultural landscapes since they are able to fix atmospheric nitrogen (Ojiem et al., 2007). The nitrogen fixation of legumes is a highly valuable feature in particular for additional improvement of degraded soils and sustainable intensification of agricultural systems (Graham and Vance, 2003; Onduru at al., 2001). Challenges aligned with climate change, such as increased rainfall variability and restricted short growing periods, make short-season grain legumes a viable option. Their adaption strategy of completing their life cycle before the onset of terminal drought seems to be advantageous for cropping with frequent droughts in semi-arid areas (Loss and Siddique, 1994). In order to identify possible niches for different grain legumes in the existing farming systems of semi-arid Eastern Kenya, understanding the resource capture, particularly the utilization of light and water over the growing period is critically important. Quantifying the temporal and spatial differences of resource use and use efficiencies of different grain legumes can be useful in identifying niches in small-holder farming systems to increase their overall farm productivity and sustainability.

The study focused on phenological development and growth of two grain legumes; common bean (Phaseolus vulgaris L.) and cowpea (Vigna unguiculata (L.) Walp.), which are widely utilized in Eastern Kenya. In addition, lablab (Lablab purpureus (L.) Sweet) was included since it is a promising neglected legume with great potential for farming in semi-arid areas (Maass et al., 2010). Common bean and cowpea are among the main sources of protein and cash income for farmers in semi-arid areas of Eastern Kenya (Muhammad et al., 2010). However, average yields are very low with 0.53 t ha-1 for cowpea and 0.6 t ha-1 for common bean (FAOSTAT, 2014) and far below the potential yield. Lablab is well suited to semi-arid areas and its tolerance to drought stress has been well established (Maass et al., 2010; Maundu et al., 1999).

To quantify growth and development of the selected grain legumes, two major concepts of resource capture were considered; first, a thermal time model to describe the effects of temperature on development and second, the relationship between accumulated intercepted solar radiation and accumulated biomass (Monteith, 1977; Sinclair and Muchow, 1999). Under non-stressed environmental conditions, the amount of dry matter

produced by a crop is linearly correlated to the amount of solar radiation, in particular photosynthetic active radiation (PAR), intercepted by the crop; with the radiation use efficiency (RUE) being the slope of the regression line (Monteith, 1977). Radiation interception is highly variable for different crops and different phenological stages throughout the growing period depending on the actual green leaf area and the extinction coefficient (k) (Sivakumar and Virmani, 1984; Thompson and Siddique, 1997; Watiki et al., 1993). The extinction coefficient describes the capability of the canopy to intercept light depending on morpho-physiological conditions (biomass partitioning, leaf angle, spatial and optical attributes of the leaves, among others). Finally, this parameter determines the light absorption by the leaf and, thereby, the light penetration into the canopy (Black und Ong, 2000). Radiation interception is, therefore, not only a matter of genetically fixed traits, in fact, influenced by environmental factors (Jeuffroy and Ney, 1997). Water stress, for example, was reported to cause a reduction in RUE in many studies of grain legumes (Craufurd and Wheeler, 1999; Muchow, 1985; Tesfaye et al., 2006). Therefore, parameters such the RUE can be used to evaluate crop performance and yield limitations of different legumes to estimate their potential in different farming systems and climatic conditions. Furthermore, this more analytical framework is needed to quantify development and growth so that these effects can be modelled better, in particular in non-optimal environments. Moreover, parameters such as the biomass partitioning coefficient, k and RUE among others are major components of crop growth models, such as the Agricultural Production System sIMulator (APSIM) and are highly valuable for model parameterization of short-season grain legumes in semi-arid areas (Keating et al., 2003).

Against this background, this study aims to compare the growth and development of three promising short-season grain legumes (common bean, cowpea and lablab) under semi-arid conditions in Eastern Kenya in response to plant density and drought to evaluate their production potential and resource capture. This was undertaken by intensively measuring plant development, biomass production, leaf area, biomass partitioning with radiation use efficiency (RUE) calculated from this information.

Material and methods

Study site

The study site is located in a semi-arid environment and is characterized by a bimodal rainfall pattern with two distinct rain seasons; the so-called short rain from October till February with a mean seasonal rainfall of about 400 mm and the long rain from March to June with approximately 300 mm of in-season rainfall. The mean annual rainfall is 700 mm and characterized by high inter- and intra-seasonal rainfall variability (Claessens et al., 2012). Mean annual temperatures vary from a mean minimum of 15 °C to a mean maximum of 26 °C, with the hottest months being October and February and the coolest month being July (Jaeztold et al., 2006). The experiments were conducted at the Kenyan Agricultural Research Institute (KARI), Katumani station in Machakos county, Kenya (1°34´55.84´´S, 37°14´42.95´´E, 1592 m asl.) during the short rains of 2012/13 and 2013/14.

Soil characterization

The trials were located on fairly well-drained reddish brown chromic Luvisols with a clay texture throughout the profile but an increased sand content at the surface layer (Jaetztold et al., 2006). The soil was slightly acid to neutral with a pH ranging from 5.5 to 7, and fairly poor in plant nutrients such as nitrogen, phosphorus, calcium and zinc, and with a relatively low organic matter content (OC ≤ 1 %) (Table 1). Prior to sowing (October 2012), pH, soil texture (hydrometer method) and soil fertility status were analyzed. A total of 10 samples per layer (0-15, 15-30, 30-60 and 60-90 cm) were randomly taken across a diagonal of the experimental site (Dalgleish and Foale, 1998) for analysis at the KARI National Agricultural Research Laboratories (NARL) in Nairobi, Kenya.

Table 1: Summary of soil texture and fertility analysis (pH, mineral nitrogen, plant-available phosphorus and exchangeable potassium) prior to sowing at KARI Katumani, Kenya.

		Soil depth [cm]			
		0-15	15-30	30-60	60-90
Soil texture analysis					
Sand	[%]	68.0	69.0	62.5	50.5
Clay	[%]	25.3	23.5	31.5	40.0
Silt	[%]	6.7	7.5	6.0	9.5
Soil fertility analysis[1]					
pH		6.5	6.5	6.2	6.0
Organic C	[%]	0.90	0.80	1.00	0.70
Total N	[%]	0.08	0.07	0.06	0.05
Phosphorus	[ppm]	33.75	31.25	20.00	15.00
Potassium	[me%]	0.87	0.81	0.65	0.35

[1] Horwitz and Latimer, 2005

Experimental design and cop management

Two experiments were designed to target temporal and spatial growth and development of three legumes, common bean, cowpea and lablab. Locally adapted and commonly used short-season varieties recommended by KARI for cultivation in small-scale farming systems in semi-arid areas were used in the experiments; KAT/B-1 and KAT X56 for common bean, M66 and KVU27-1 for cowpea and DL1002 and cv. Highworth for lablab.

During short rains 2012/13 season, two bean (KAT/B-1 and KAT X56), two cowpea (M66 and KVU27-1) and one lablab (DL1002) variety were included in the experiment. In short rains 2013/14 season, one bean (KAT X56) and one cowpea (M66) variety were used because of very similar growth and development patterns when comparing varieties within one species. In addition to the locally adapted lablab variety DL 1002, the well-known short-season lablab cv. Highworth was used and included in the water response trial. Cowpea and bean seeds were inoculated with *Rhizobium phaseoli* strain CIAT 899, while lablab was inoculated with USDA 3605 strain prior to sowing.

The design of the experiment was complete randomized block with four replications. Individual plots were 5 m by 2.5 m for bean and cowpea and 5 m by 3.2 m for lablab in order to provide enough plants for biomass determination throughout the experiment. Seeds were sown at a depth of 30 mm. Triple superphosphate (TSP) was applied during planting at a rate of 20 kg P ha^{-1} as well as urea at a rate of 10 kg N ha^{-1} for successful seedling establishment. Seeds were initially planted at a high rate and plots were later thinned to the required densities after the appearance of the first true leaf. Weeds were controlled using a pre-plant knockdown herbicide (Roundup®) before planting and by hand during the growing period, to minimize competition for water, nutrients and sun light. Duduthrin (Lambda-cyhalothrin 17.5 gl^{-1}), Thunder (Bayer; Imidacloprid 100 g/l + Beta-cyfluthrin 45 g/l) and Marshal (Syngenta, 35% Carbosulfan) were applied at different stages of plant growing period to control leaf-eating insects and aphids on cowpea and lablab.

Seeds were sown at the onset of the rainy season on 14th November in 2012 for the 2012/13 short rains and on 5th November in 2013 for the 2013/14 season.

Plant density trial

The objective of the density experiment was to quantify the effect of plant density on canopy development, biomass accumulation and partitioning to evaluate resource use and use-efficiency of the different legumes. Therefore, three different plant densities were included in this experiment. The treatment 'medium' (common bean and cowpea: 10 plants m^{-2}, lablab: 4.2 plants m^{-2}) followed the recommendations by KARI (2006) for farming in semi-arid areas, while 'high' was double and 'low' only half of the recommended density. All plots received additional irrigation of up to 50 mm of water per week through drip irrigation.

Water response trial

The water response trial aimed to estimate the impact of water availability on biomass development, partitioning as well as radiation use and use efficiency. The trial consisted of three water treatments; purely rainfed, partly irrigated (total 50 mm of water per week with additional drip irrigation till bud formation, i.e., onset of flowers), fully irrigated (total of 50 mm of water per week with additional drip irrigation throughout the growing period) (Table 2). All plants were established using the recommended density ('medium' from the plant density trial, (KARI, 2006)).

Table 2: Details Summary description of the treatments included in the plant density and water response trial at KARI Katumani, Machakos, Kenya during the short rains of 2012/13 and 2013/14.

Season	Species	Water regime	Irrigation [mm]	In-crop rainfall [mm]	Irrigation + rainfall [mm]
2012/13	Bean	fully irrigated	270	156	426
		partly irrigated	150	156	306
		rainfed	-	156	156
	Cowpea	fully irrigated	300	190	490
		partly irrigated	225	190	415
		rainfed	0	190	190
	Lablab	fully irrigated	345	190	535
		partly irrigated	210	190	400
		rainfed	-	190	190
2013/14	Bean	fully irrigated	240	259	499
		partly irrigated	60	259	319
		rainfed	-	259	259
	Cowpea	fully irrigated	330	259	589
		partly irrigated	180	259	439
		rainfed	-	259	259
	Lablab	fully irrigated	345	339	684
		partly irrigated	180	339	519
		rainfed	-	339	339

Data collection

Meterological data

Meteorological data recorded during the experimental period included rainfall and daily minimum and maximum temperatures. Records on solar radiation were obtained from the meteorological station at KARI Katumani, which was about 150 m away from the experimental field.

Biomass and LAI sampling

Plants were destructively harvested for above-ground biomass determination every second week after plant establishment (two weeks after planting) on 5 (bean), 6 (cowpea) and 7 (lablab) occasions during the 2012/13 growing period and on 6 (bean), 7 (cowpea) and 8 (lablab) dates during the 2013/14 growing period, including time of 50 % flowering and physiological maturity (2012/13 growing period: 28th November, 12th December, 26th December, 9th January, 23rd January, 6th February, 20th February; 2013/14 growing period: 20th November, 4th December, 18th December, 1st January, 15th January, 28th January, 6th February, 18th February). The different numbers of sampling occasion for the different legumes were caused by the distinct development times.

On each sampling date, 2 plants were randomly cut right above the soil surface from each subplot (4) and manually separated into leaf, stem, flowers, pod-wall and grain. Afterwards, plant parts were dried at 60 °C for 48h for dry matter (DM) determination.

Leaf area index (LAI) and photosynthetic active radiation (PAR) above and below the canopy were measured at all four subplot per legume and treatment in intervals of 7 to 10 days (dependent on daily cloudiness) after plant establishment till complete leaf senescence using an AccuPAR LAI ceptometer (Decagon Devices, model LP-80). For the spot measurement the LAI ceptometer was placed at right angle to the crop rows at the soil surface. Measurements were taken between 12:00 and 14:00 h local time (GMT+ 3) and repeated 10 times at each subplot.

Phenological development

Furthermore, data were collected on emergence and phenology (first bud formation, flowering, end of flowering and maturity) in days after planting (DAP). Flowering was defined as 50 % of plants with open flowers, pod set was 50 % of plants with visible pods, end of flowering was 50% of plants with no more flowers, and physiological maturity when 90% of the pods were dry.

Data analysis and calculations

Thermal time

The time from and between different developmental stages was determined in thermal time expressed in degree days (T_t, °Cd). Thermal time was computed using the algorithms used in CERES-Maize, which divides each day into eight 3-h time periods on the basis of daily inputs of maximum and minimum temperatures (Jones et al., 1986). The thermal time concept is based on the assumption that growth is a positive linear process between base temperature and optimal temperature. At optimal temperature, processes proceed at their maximum rate. From the optimal temperature towards the maximum temperature, there is a declining negative relationship (Monteith, 1977). Base, optimal and maximal temperatures (T_b, $T_{optimal}$, T_{max}, °C) were assumed to be 9, 25 and 37 °C, respectively, for beans; 10, 34 and 44 °C, respectively, for cowpea; and 10, 30 and 40 °C, respectively, for lablab (Hill et al., 2006; Robertson et al., 2002; Turpin et al., 2003).

Biomass partitioning

The distribution of biomass between leaves and stem was described using the biomass partitioning coefficient, which was determined by regressing the biomass of green leaves against the total above-ground vegetative biomass. The slope of the regression was estimated to be the biomass partitioning coefficient (Robertson et al., 2002; Soltani et al., 2006). This represents the allocation of biomass distributed to different organs as implemented crop simulation models such as APSIM.

Harvest index (HI)

The harvest index (HI) represents the ratio of grain yield / total above-ground biomass (TDM). The comparison of the denominator, i.e. TDM at flowering (maximum biomass production) or TDM at harvest was also considered. Since grain legumes often drop their leaves towards the end of the growing period, HI calculated from biomass at flowering can give a more representative and better comparable ratio.

Radiation use efficiency (RUE)

From the measured PAR values, the radiation interception fraction (f) was calculated by taking into account the assumption that only 6 % of visible light is reflected by green canopy (Dingkuhn et al., 1999). According to Lambert-Beer's law, the radiation intercepted fraction (f) is related to the LAI, with k being the extinction coefficient.

$$f = 1 - exp^{(-kLAI)}$$

The extinction coefficient can be estimated by least-square regression analysis: calculating the slope of the relationship between the natural logarithm of the transmitted PAR ($PAR_{trans} = 1 - f$) $ln(PAR_{transm})$ and the LAI (Dingkuhn et al., 1999; Szeicz, 1974).

Cumulative intercepted radiation was determined by summing up the incoming solar radiation measured by the meteorological station for each day after emergence after determining the PAR fraction considering the assumption that 45 % of solar radiation is PAR (Meeket al., 1984). RUE was calculated as the slope of the regression of the accumulated biomass (above-ground biomass, including leaves and stem as DM in gm^{-2}) and cumulative intercepted radiation (Sinclair and Muchow, 1999). The accumulated PAR was calculated from the cumulated daily PAR and the previously estimated k by Lambert-Beer's law. Values for RUE were assessed for the three legumes and different density and water regimes included in the experimental trials.

Statistical analysis

Biomass partitioning coefficient, yield and HI data were analyzed using analysis of variance (ANOVA) and tests of significance were conducted using post-hoc multiple comparison Tukey test to identify effects of plant density and water regime within species. Test of homogeneity was conducted to compare the regression coefficient RUE. The significant differences among treatments were compared with the critical difference at 5% level of probability. All statistical analyses were computed using R 2.15.1 (R 2008).

Results

Weather

Temperature patterns were fairly similar in the two short rainy seasons 2012/13 and 2013/14 (from 15th October to 15th March), with mean minimum temperatures of 15 °C and mean maximum temperatures of 31 °C. Absolute minimum temperatures measured within each season were 10 and 11 °C, while absolute maxima were 42 and 40 °C in 2012/13 and 2013/14, respectively (Figure 1). In both years, average temperature was 23 °C. Rainfall intensity and distribution were different in the two rainy seasons 2012/13 and 2013/14. In the growing period (15th October to 15th March), rainfall was below the long-term average (Claessens et al., 2012; Rao and Okwach, 2005) in 2012/13 with 262 mm only, though relatively evenly distributed between November and January but no rain in February. During the short rains of 2013/14, total rainfall was above long-term average, and almost 100 mm more rain was recorded than in the previous season, in total 354 mm from mid-October to mid-March. In 2013/14, rainfall was distribution was poor, with 220 mm falling between end-November to end-December as heavy rains and a long in-growing period dry spell occurring from 22nd December to 6thFebruary. Because of the high intensity of rain showers occurring at the end of 2013, it was mostly cloudy leading to reduced total solar radiation in the 2013/14 rainy season in comparison to the 2012/13 one.

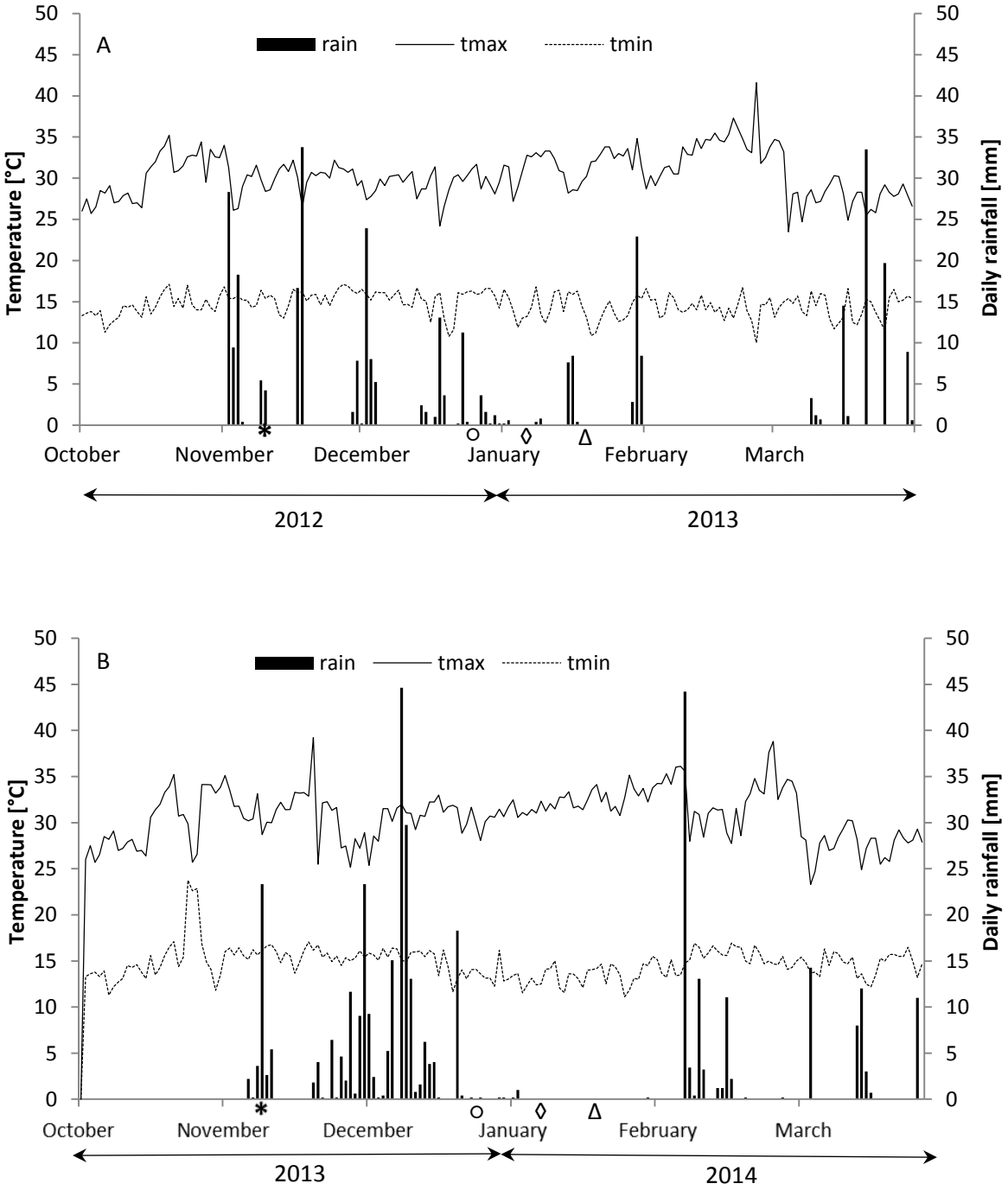

Figure 1: Daily minimum and maximum temperatures and rainfall during the short rains seasons at KARI Katumani, Kenya, (A) 2012/13 and (B) 2013/14.
* Planting date
○ Common bean harvest
◊ Cowpea harvest
Δ Lablab harvest

Phenological development

Pronounced temporal differences were observed in the phenological development of common bean, cowpea and lablab (Figure 2). Only time to emergence was fairly similar for all legumes and took approximately 7 days. In both seasons, the duration from planting to emergence, first bud formation, first flowering, 50 % flowering, end of flowering and physiological maturity were shortest for common bean. Whereas lablab flowered earlier (43–47 DAP) than cowpea (47–54 DAP), it took more time to reach physiological maturity (98–104 DAP). Common bean proved to be a true short-season crop, and first flowering was observed already 37–41 DAP with grains ready to harvest at 69–78 DAP. Cowpea took about 84–92 DAP to maturity, but the duration of grain filling was fairly short in comparison to lablab. From 50 % flowering to physiological maturity only three weeks passed, in comparison of six weeks as observed for lablab.

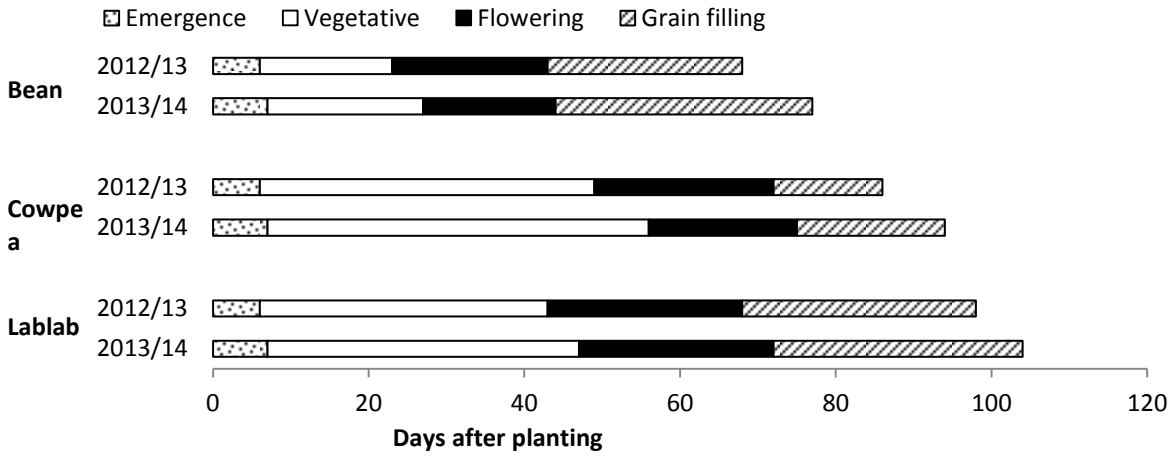

Figure 2: Phenological development including emergence, vegetative phase, flowering and maturity of common bean, cowpea and lablab for the 2012/13 and 2013/14 growing periods at KARI Katumani, Kenya.

Similar trends were observed for phenological development expressed in thermal time (Table 3). Plant development, including flowering and physiological maturity, was delayed for all legumes in the growing period of the short rains in 2013/14, compared with the 2012/13 season by about 7 days or 50 to 100 °Cd depending on species and phenological stage. However, significant differences in the phenological development between the different treatments (density and water regime) for the species were not observed.

Table 3: Phenological development including emergence, floral bud formation, first, 50 % and end of flowering and maturity of common bean, cowpea and lablab expressed as thermal time in degree days (average over two seasons 2012/13 and 2013/14) at KARI Katumani, Kenya.

Thermal time to…[°Cd]	Bean	Cowpea	Lablab
Emergence	94.1	49.4	83.0
Bud formation	348.7	535.2	561.4
First flowering	449.6	606.5	658.6
50 % flowering	521.5	672.3	723.8
End of flowering	592.6	754.3	861.8
Maturity	948.8	937.8	1237.2

LAI and fraction of PAR intercepted

Differences in the spatial development of common bean, cowpea and lablab became obvious in the change of LAI and fraction of intercepted PAR over the growing period in both experiments (plant density trial: Figure 3 and 5; water response trial: Figure 4 and 5). In general, it was observed that the dimensions in LAI largely differed among legumes; maximum LAI was achieved at flowering even if the actual time of flowering was different for all the legumes. For all species, LAI increased from planting to end of flowering and decreased rapidly from the beginning of grain filling to physiological maturity (Figure 2). Interestingly, the speed of increase and reduction in LAI over time varied among the legumes, indicating differences in leaf appearance rate and overall canopy structure.

Whereas the LAI of cowpea dropped rapidly immediately after flowering, lablab seemed to maintain almost maximum LAI for some time even after 50% flowering (Figure 3). The highest LAI values (> 4) were, however, recorded for cowpea for the fully irrigated treatment at early flowering (56 DAP). A strong effect of plant density in LAI was detected for common bean with faster increase of LAI and higher values reached at high plant densities compared with medium and low density treatments. In contrast, the effect of plant density was fairly weak for cowpea (Figure 3). The response to the different water treatments was comparatively low in 2013/14, whereas in 2012/13 the LAI of cowpea, for example, was reduced from > 4 to < 2 under rainfed conditions and halved for beans from > 2 to < 1 at the maxima. The legumes, however, responded differently when supplementary irrigation was stopped at bud formation, strongly depending on the rainfall patterns within each season (Figure 4).

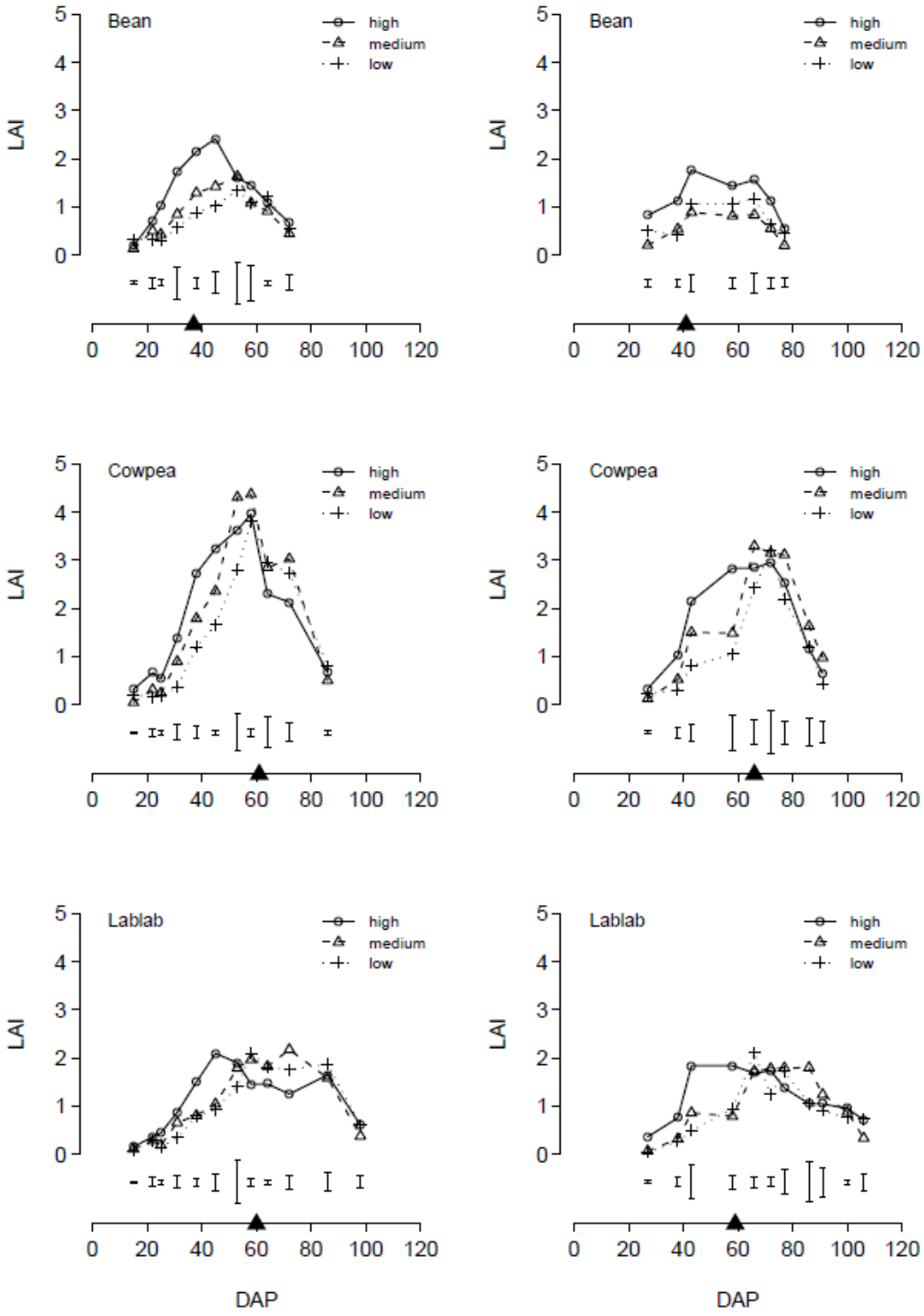

Figure 3: Change in LAI over the growing periods 2012/13 (left) and 2013/14 (right) for common bean, cowpea and lablab for three plant densities at KARI Katumani, Kenya. Standard deviation is illustrated representative for the ´medium` treatment.
▲50 % flowering

Similar trends as observed and described for the change in LAI over the growing period were reflected in the change of the fraction of intercepted PAR (Figure 5). Cowpea was able to intercept almost 100 % of incoming PAR during the time of flowering; from early bud formation at 40 DAP to the start of grain filling at about 70 DAP, indicating a very high potential for above-ground biomass production and surface coverage. Lablab maintained fairly high ratios of intercepted PAR (0.8) for a relatively long period covering flowering and grain filling (40–85 DAP). All the legumes planted at high densities reached maximum levels of fractional intercepted PAR earlier, indicating a fast canopy closure and good leaf soil coverage at high planting densities. However, higher densities affected only the early stages of seasonal fractional PAR interception. At later stages, f was leveled off and fairly equal for all plant densities indicating some compensation by the low-density crop through greater branching and increased leaf area production per plant. The water treatment rather influenced the seasonal fractional PAR interception at later developmental stages from flowering onwards. Under rainfed conditions for instance, the decrease of seasonal fractional PAR interception from bud formation onwards was evident for all the legumes, but in particular severe for common bean (Figure 5). For lablab instead, f continuously increased until the end of flowering (> 80 DAP) even under rainfed conditions, the maximum levels of the fully irrigated plants were, however, not reached (Figure 5). Stopping the supplementary irrigation (partly irrigated treatment) at bud formation had little impact on the seasonal fractional PAR interception, indicating that water stress in early reproductive stages was more important than in later reproductive stages.

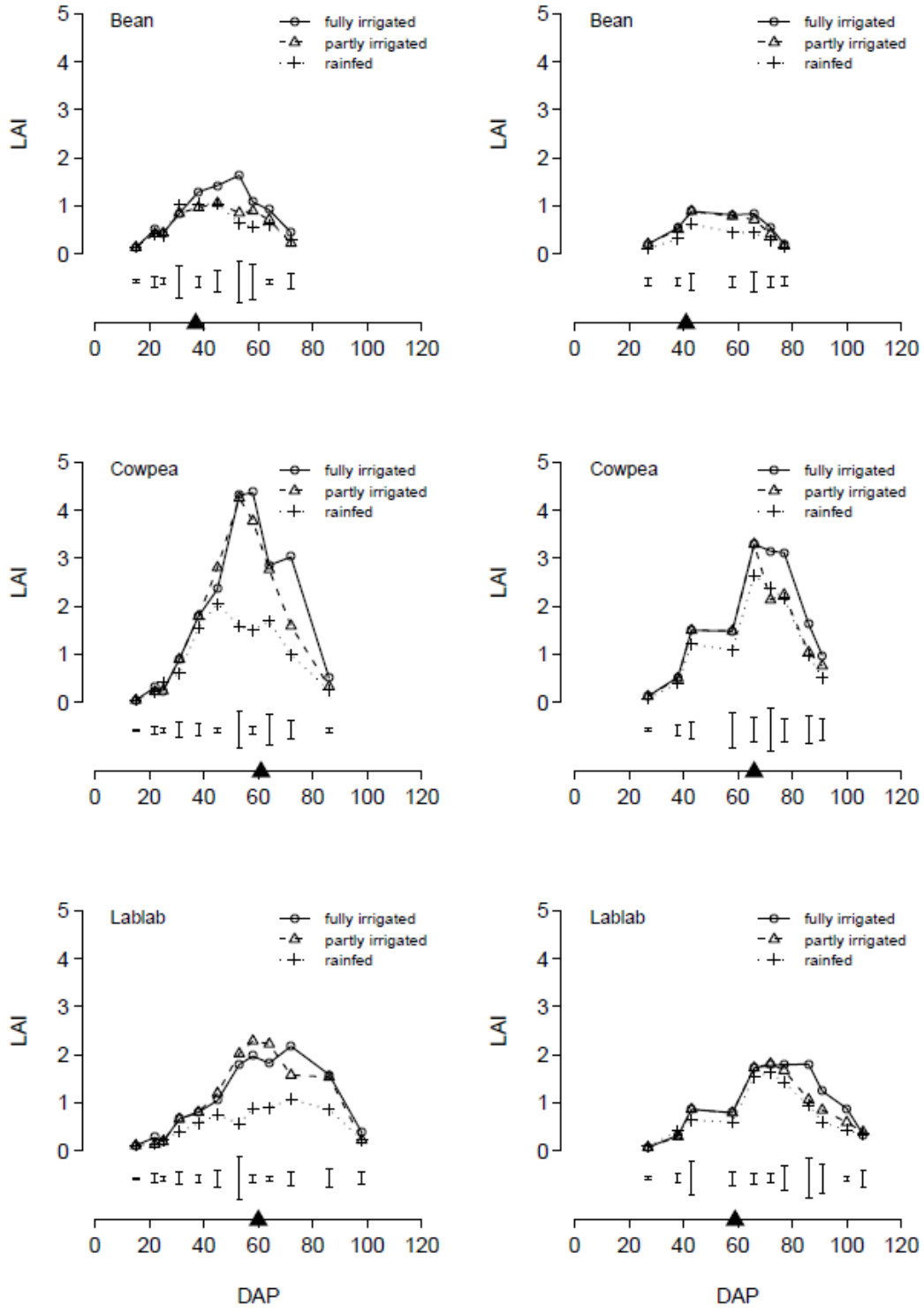

Figure 4: Change in LAI over the growing periods 2012/13 (left) and 2013/14 (right) for common bean, cowpea and lablab for three watering regimes at KARI Katumani, Kenya. Standard deviation is illustrated representative for the ´fully irrigated` treatment.
▲50 % flowering

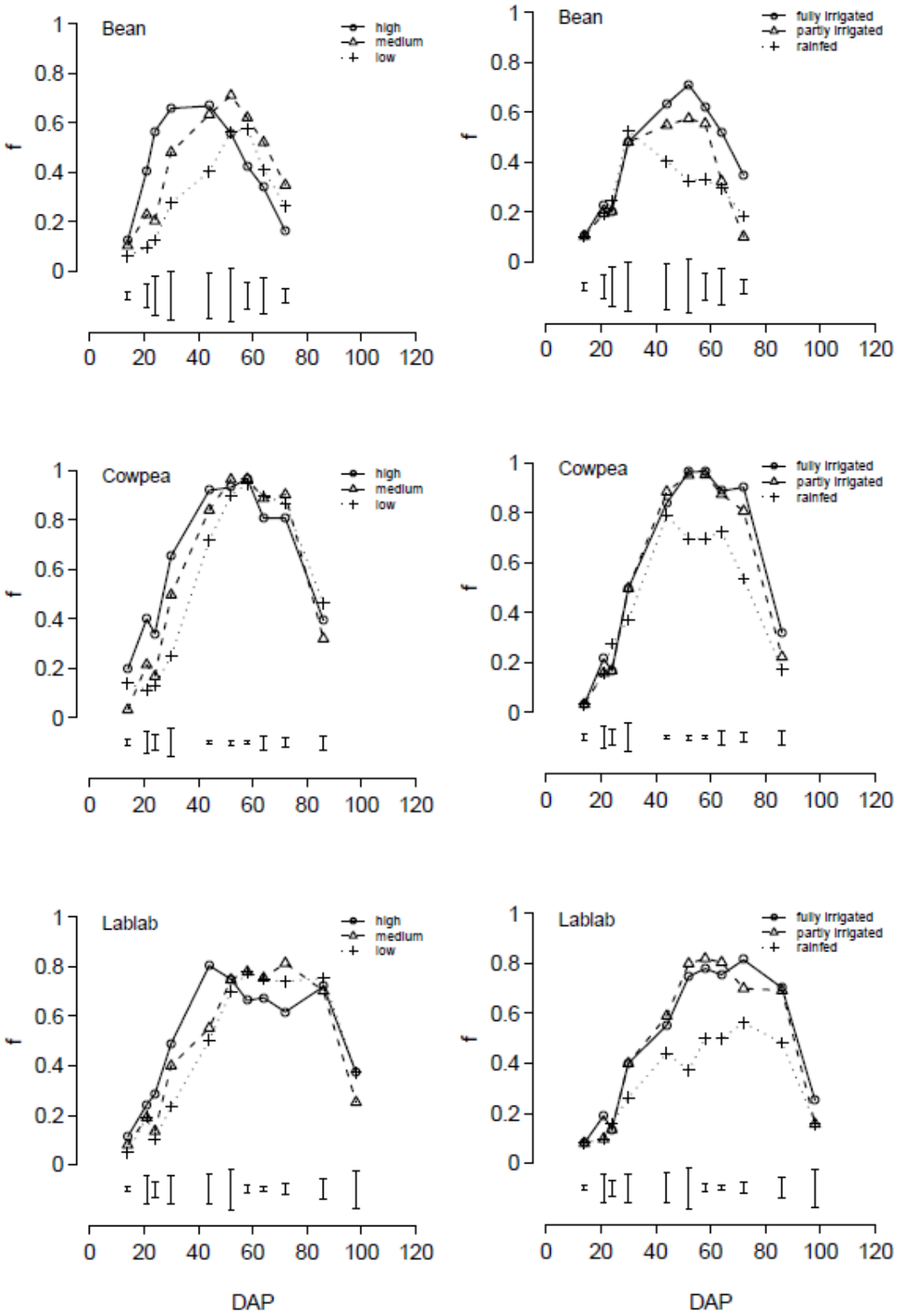

Figure 5: The fraction of PAR intercepted (***f***) over the growing period of 2012/13 for common bean, cowpea and lablab for three plant densities (right) and three water regimes (left) at KARI Katumani, Kenya. Standard deviation is illustrated representative for the ´medium` treatment (right) and the ´fully irrigated` treatment (left).

3.4 Biomass development and partitioning

The magnitudes of LAI and light interception are reflected in above-ground biomass accumulation (Figure 6 and 7). The total above-ground biomass production was highest by cowpea (400 – 600 g m^{-2} at maturity), followed by lablab (300 – 700 g m^{-2} at maturity) and lowest for common bean (300 – 500 g m^{-2} at maturity). Plant density had only a significant effect on the above-ground biomass accumulation of cowpea and lablab, indicating a vigorous growth habit and higher degree of phenological plasticity. In contrast, biomass production of common bean was fairly similar for all three plant densities. High plant densities led to a very high and statistically significant increase in biomass accumulation for lablab in 2013/14, for instance, from about 350 to almost 700 g m^{-2}. However, the final biomass production at maturity of cowpea was similar (in 2013/14) or higher (2012/13) if planted at ´medium` density if compared to ´high` density, indicating a high growth compensation capability and a self-regulatory mechanism to avoid an increased competition for limited resources(Figure 6). Low plant densities led to a reduction in total above-ground biomass for cowpea and bean, indicating that even a similar overall canopy closure (represented in similar observed $\boldsymbol{f}$) in space did not result in similar biomass yields per area. The effect of supplementary irrigation on biomass production varied among the legumes. Whereas above-ground biomass production was more than doubled for cowpea (580 g DM m^{-2}) and significantly increased in 2012/13 under fully irrigated conditions at flowering and physiological maturity compared to rainfed conditions, the increase was comparatively low and not significant for common bean and lablab (Figure 7).

Final yield was not determined by leaf area and fraction of PAR interception alone, but in fact influenced by the allocation of biomass between plant organs. Common bean had the highest biomass partitioning coefficient (0.48). Cowpea partitioned, on average, 45 % of the total biomass to the leaves, whereas lablab had only 36 %. Plant density had only an effect on biomass partitioning of common bean and lablab, whereas for cowpea no significant changes were observed with plant density (Table 4). Further a reduction in biomass partitioning coefficient was observed at low and high densities for lablab, displaying a strong plant density effect. Plotting biomass partitioning over time gives evidence of the leaf-stem and vegetative vs. reproductive biomass investment of the species (data not shown) indicating that, even if total above-ground biomass production at high densities of lablab is very high, allocation towards grains remains comparatively low from grain filling to physiological maturity. For common bean and lablab, a significant reduction in the biomass partitioning coefficient was observed under full irrigation compared with rainfed conditions, indicating a higher investment in vegetative plant organs in relation to reproductive plant parts (Table 5).

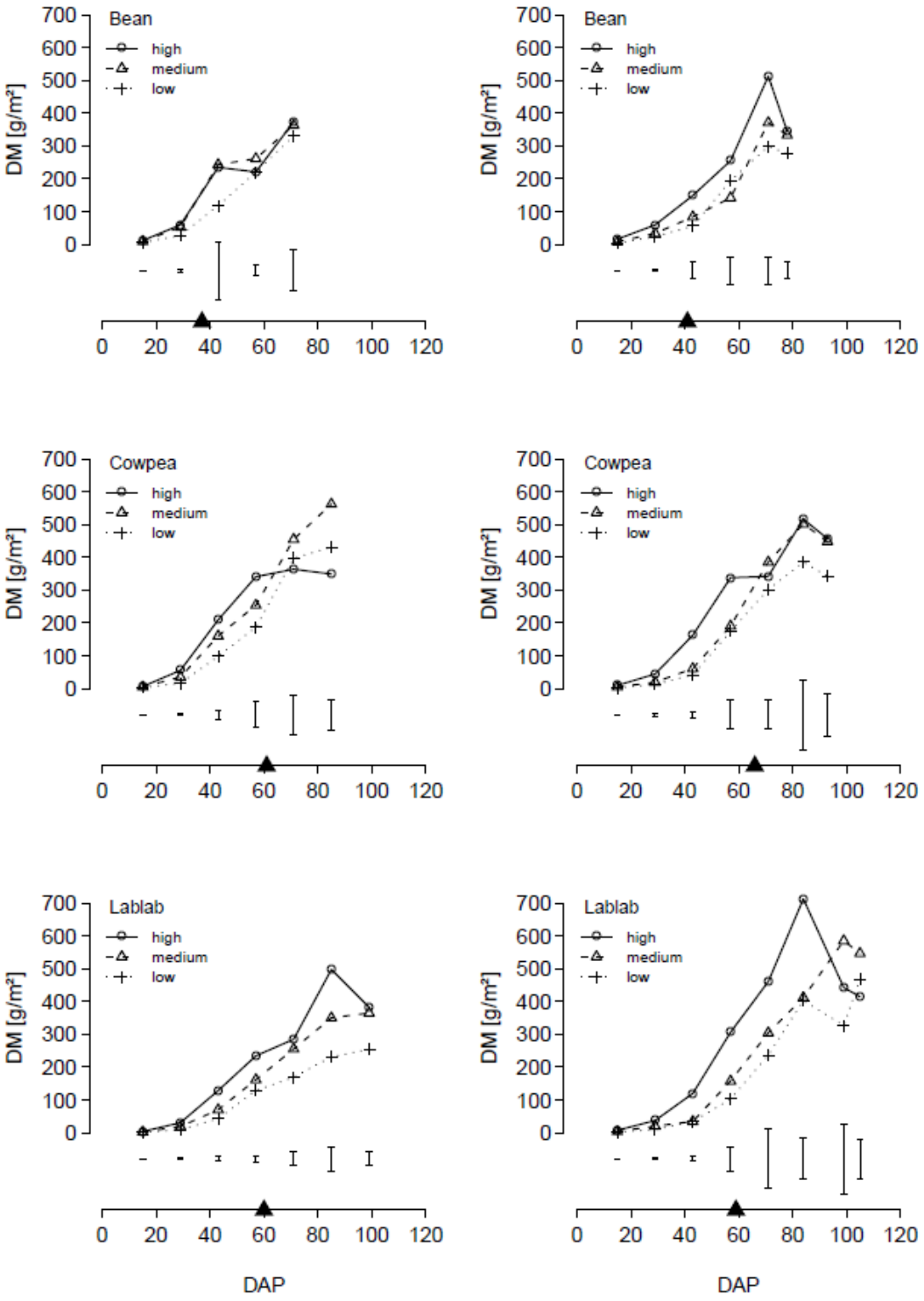

Figure 7: Seasonal above-ground biomass (as dry matter, DM) accumulation during the growing periods of 2012/13 (left) and 2013/14 (right) for common bean, cowpea and lablab for three plant densities at KARI Katumani, Kenya. Standard deviation is illustrated representative for the ´medium` treatment.
▲50 % flowering

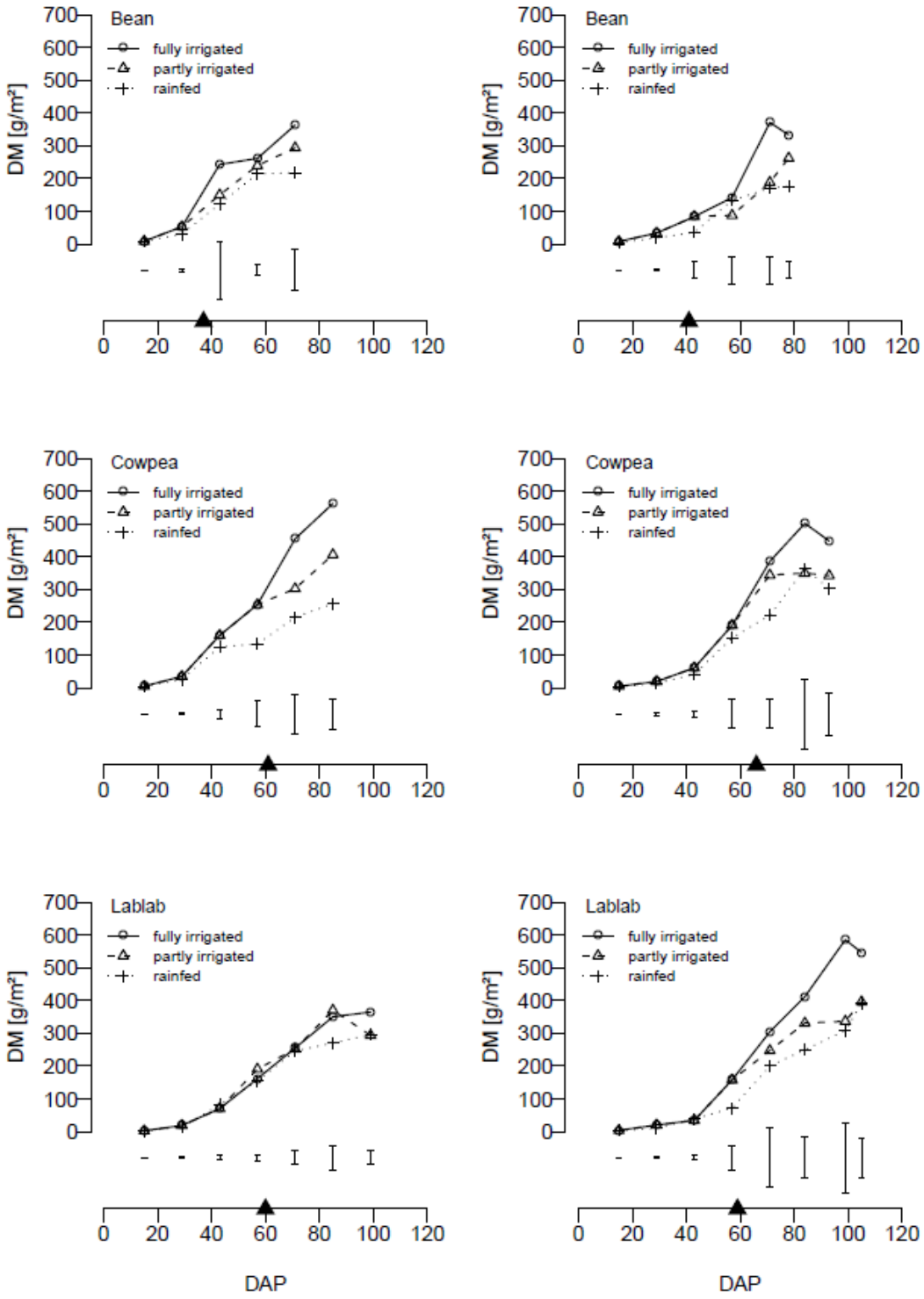

Figure 8: Seasonal above-ground biomass (as dry matter, DM) accumulation during the growing periods of 2012/13 (left) and 2013/14 (right) for common bean, cowpea and lablab for three water regimes at KARI Katumani, Kenya. Standard deviation is illustrated representative for the ´fully irrigated` treatment.
▲50 % flowering

Table 4: Biomass partitioning coefficient for common bean, cowpea and lablab calculated for three plant densities at KARI Katumani, Kenya. Calculated from combined data over two growing seasons (2012/13 and 2013/14).

Plant density	Bean	Cowpea	Lablab
Low	0.49 [ab]	0.45 [a]	0.34 [b]
Medium	0.52 [a]	0.42 [a]	0.39 [a]
High	0.47 [b]	0.43 [a]	0.34 [b]
Mean	**0.48**	**0.43**	**0.36**

[a,b,c] means within a column followed by the same letters are not significantly different according to Tukey's multiple-comparison test *(P* < 0.05)

Table 5: Biomass partitioning coefficient for common bean, cowpea and lablab calculated for three water regimes at KARI Katumani, Kenya. Calculated from combined data over two growing seasons (2012/13 and 2013/14).

Water regime	Bean	Cowpea	Lablab
Fully irrigated	0.47 [b]	0.41 [a]	0.37 [b]
Partly irrigated	0.53 [a]	0.43 [a]	0.41 [a]
Rainfed	0.52 [a]	0.42 [a]	0.39 [ab]
Mean	**0.48**	**0.43**	**0.36**

[a,b,c] means within a column followed by the same letters are not significantly different according to Tukey's multiple-comparison test *(P* < 0.05)

The radiation use efficiency (RUE in g MJ^{-1} PAR) was predicted from the interpolation of the cumulative PAR against biomass production with the coefficient of determination being fairly high for species, plant density and water regime (R^2 > 0.65). Best fits were estimated for lablab with R^2 > 0.76. RUE estimates differed significantly (P<0.05) among plant densities (Figure 8) and water regimes (Figure 9). For common bean, RUE was generally high and ranged from 0.92 under high plant density to 1.73 g MJ^{-1} PAR under low plant density (Figure 8). Lablab had the lowest RUE ranging from 0.62 to 0.92g MJ^{-1} PAR from low to high plant densities. The water regime had only a significant effect on RUE in common bean and cowpea, whereas no change in RUE with the irrigation level was observed for lablab, indicating less impact of plant water status on RUE in comparison to common bean and cowpea (Figure 9). Under rainfed conditions, RUE was significantly lower than compared to the fully irrigated treatment reaching only 0.49 and 0.54 g MJ^{-1} PAR for common bean and cowpea, respectively.

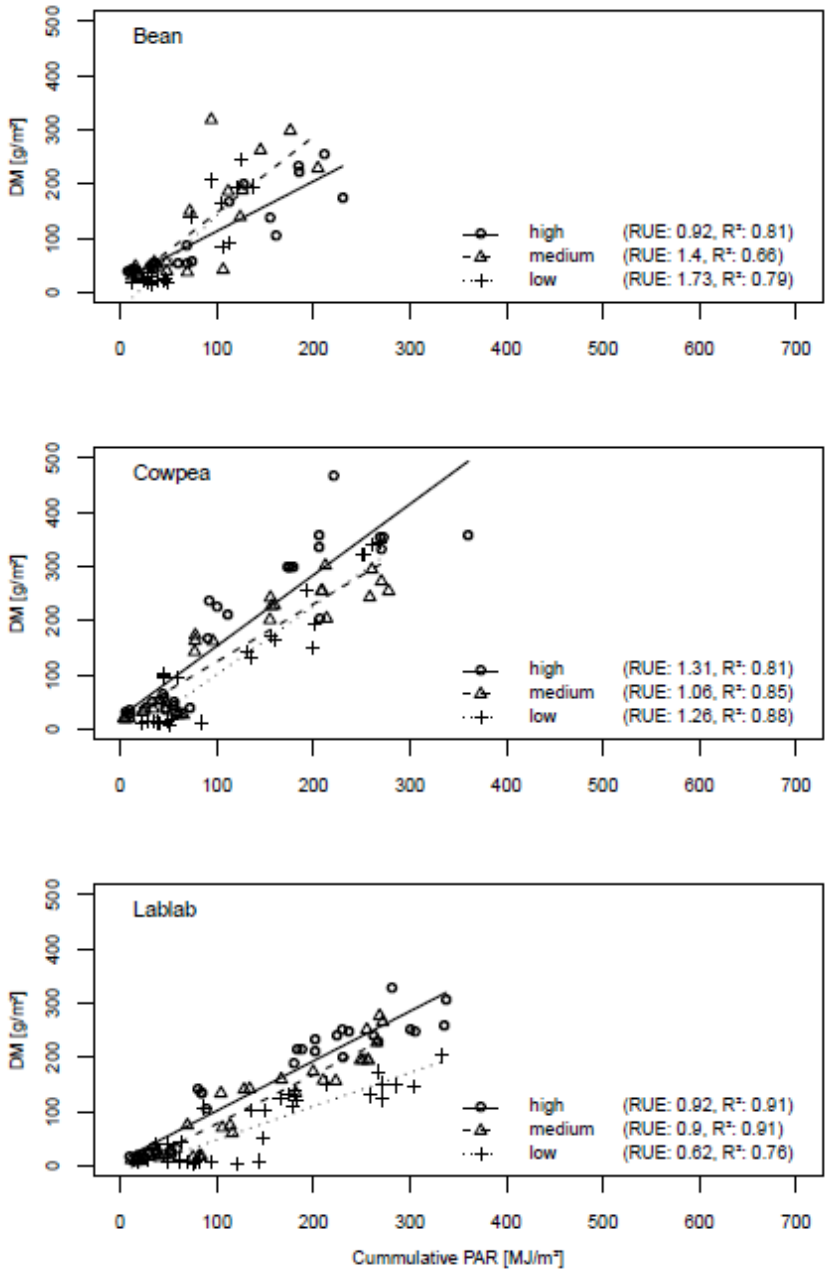

Figure 9: Radiation use efficiency (RUE) derived from the regression analysis of above-ground biomass in dry matter (DM) and cumulative PAR for common bean, cowpea and lablab for three plant densities calculated from data combined over two growing seasons (2012/13 and 2013/14) at KARI Katumani, Kenya.

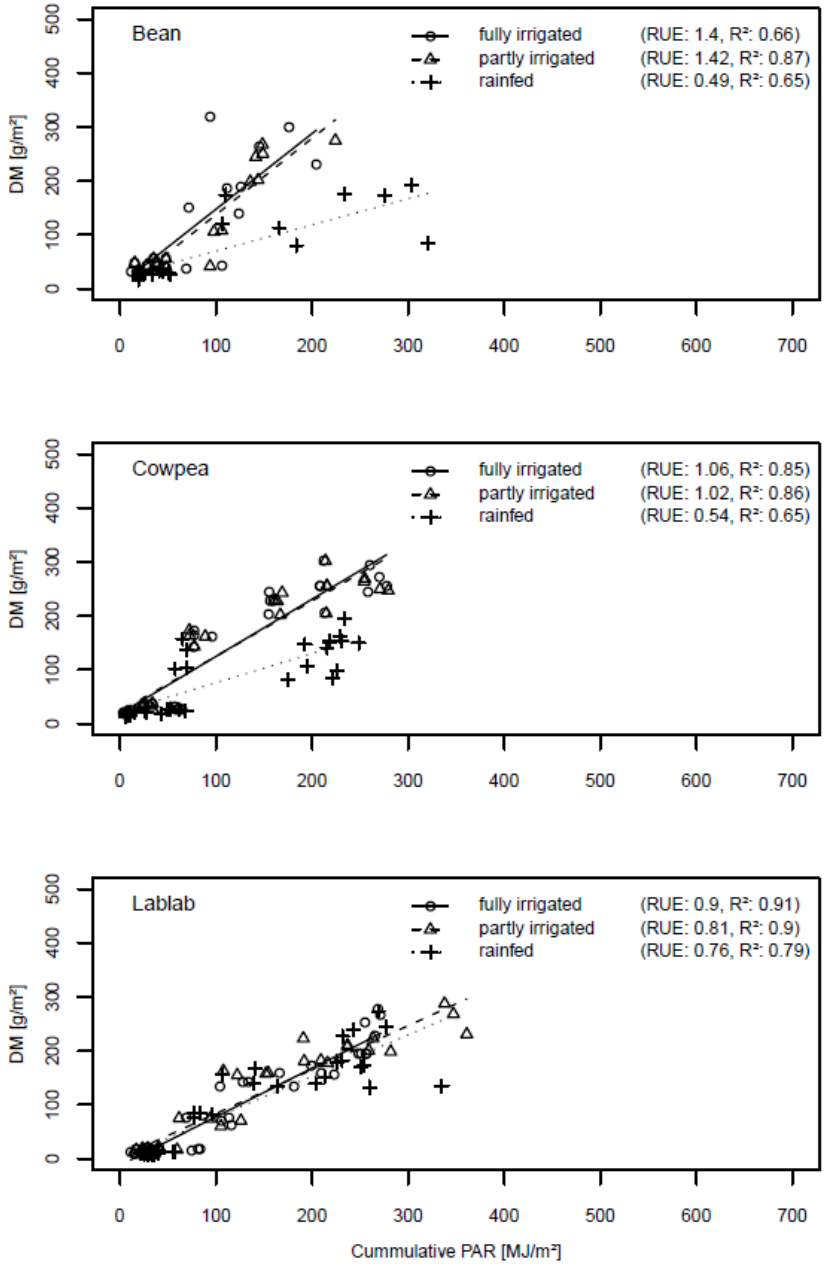

Figure 10: Radiation use efficiency (RUE) derived from the regression analysis of above-ground biomass in dry matter (DM) and cumulative PAR for common bean, cowpea and lablab for three water regimes calculated from data combined over two growing seasons (2012/13 and 2013/14) at KARI Katumani, Kenya.

Seed yield and harvest index

Observed grain yield varied strongly between the two rainy seasons. Common bean and cowpea had higher grain yields in 2012/13 than 2013/14, while lablab had highest yields in 2013/14. The effects of different planting densities and their magnitudes varied among species (Table 6). In 2012/13, planting densities had no significant effect on bean yield, whereas in 2013/14 yields were reduced by almost 20 % if planted at low densities compared with ´medium` and ´high` plant density. The same was true for cowpea where yields were reduced by 28 and 25 % in 2012/13 and 2013/14, respectively, at low plant densities. For lablab, yields were significantly reduced by lower and higher planting densities in 2012/13 but only by high densities in 2013/14. The significant decrease of lablab grain yield (-27 %) planted at high densities indicated continuous investment in vegetative growth throughout the growing period reflected in the comparatively low biomass partitioning coefficient and high share of leaf biomass. For all species, yields were always highest under full irrigation and significantly reduced under rainfed condition by about 50, 30–50 and 20-30 % for common bean, cowpea and lablab, respectively (Table 7).

The effects of plant density and watering regime on grain yield were not reflected similarly in the harvest index. In 2012/13, the share of grain biomass in total biomass at harvest was higher than 50% for common bean, cowpea, and lablab, except for lablab planted at high densities or under water limited conditions.

The mean HI of lablab decreased under high planting densities compared with medium and low densities in both years, supporting the hypothesis of increased vegetative growth in dense plant stands. The different water regimes did not change HI of common bean and cowpea. Surprisingly, HI for lablab was highest under supplementary irrigation in 2012/13 but lowest in 2013/14, indicating a high phenological plasticity aligned with environmental conditions. When grain yield was set in relation to maximum TDM at flowering, calculated values of HI were lower than the ones for HI determined from TDM at harvest (Table 6 and 7). Since biomass production of cowpea was highest at flowering in relation to grain yield, calculated HI (0.38 and 0.36 in 2012/13 and 2013/14, respectively) was lower than for beans (0.49 and 0.50 in 2012/13 and 2013/14, respectively) and lablab (0.40 and 0.42 in 2012/13 and 2013/14, respectively).

Table 6: Grain yield and harvest index (HI) calculated from total above-ground biomass at harvest and maximal above-ground biomass at flowering in brackets for common bean, cowpea and lablab for three plant densities from 2012/13 and 2013/14 seasons at KARI Katumani, Kenya.

Season	Plant density	Grain yield [kg ha^{-1}]			HI					
		Bean	Cowpea	Lablab	Bean		Cowpea		Lablab	
2012/13	low	1821.8 ^{a}	2192.0 ^{a}	1271.4 ^{a}	0.55 ^{a}	(0.61 ^{a})	0.51 ^{a}	(0.36^{ab})	0.50 ^{a}	(0.52 ^{a})
	medium	1888.2 ^{a}	3060.6 ^{c}	1932.6 ^{b}	0.52 ^{a}	(0.44 ^{b})	0.54 ^{a}	(0.40 ^{a})	0.53 ^{a}	(0.43^{b})
	high	1859.4 ^{a}	1863.7 ^{b}	1463.9 ^{a}	0.50 ^{a}	(0.44 ^{b})	0.53 ^{a}	(0.34 ^{b})	0.38 ^{b}	(0.34^{c})
	mean	**1856.5**	**2372.1**	**1556.0**	**0.52**	**(0.49)**	**0.53**	**(0.37)**	**0.47**	**(0.43)**
2013/14	low	1597.1 ^{b}	1647.2 ^{b}	2139.3 ^{a}	0.58 ^{a}	(0.45 ^{b})	0.48 ^{a}	(0.35 ^{a})	0.43 ^{a}	(0.47 ^{a})
	medium	1955.7 ^{a}	2210.2 ^{a}	2351.7 ^{a}	0.59 ^{a}	(0.58 ^{a})	0.49 ^{a}	(0.36 ^{a})	0.43 ^{a}	(0.44 ^{a})
	high	1882.1 ^{a}	2188.9 ^{a}	1706.5 ^{b}	0.55 ^{a}	(0.42 ^{b})	0.48 ^{a}	(0.39 ^{a})	0.41 ^{a}	(0.27^{b})
	mean	**1811.6**	**2015.4**	**2065.8**	**0.57**	**(0.48)**	**0.48**	**(0.37)**	**0.43**	**(0.46)**

^{a,b,c} means within a column followed by the same letters are not significantly different according to Tukey's multiple-comparison test ($P < 0.05$)

Table 7: Grain yield and harvest index (HI) calculated from total above-ground biomass at harvest and maximal above-ground biomass at flowering in brackets for common bean, cowpea and lablab for three water regimes from 2012/13 and 2013/14 seasons at KARI Katumani, Kenya.

Season	Water regime	Grain yield [kg ha^{-1}]			HI					
		Bean	Cowpea	Lablab	Bean		Cowpea		Lablab	
2012/13	fully irrigated	1888.2 ^{a}	3060.6 ^{a}	1932.6 ^{a}	0.52 ^{a}	(0.44^{b})	0.54 ^{a}	(0.40^{a})	0.53 ^{a}	(0.43 ^{a})
	partly irrigated	1557.3 ^{b}	1967.8^{b}	1438.0^{b}	0.53 ^{a}	(0.51^{a})	0.49 ^{a}	(0.39 ^{a})	0.49 ^{a}	(0.36^{ab})
	rainfed	1107.0^{c}	1384.5^{c}	1234.4^{b}	0.51 ^{a}	(0.48^{ab})	0.54 ^{a}	(0.39 ^{a})	0.42 ^{b}	(0.33^{b})
	mean	**1517.5**	**2137.6**	**1535.0**	**0.52**	**(0.49)**	**0.52**	**(0.37)**	**0.48**	**(0.43)**
2013/14	fully irrigated	1955.7^{a}	2210.2^{a}	2351.7 ^{a}	0.59 ^{a}	(0.58^{a})	0.49 ^{a}	(0.36 ^{ab})	0.43 ^{c}	(0.44 ^{a})
	partly irrigated	1460.3 ^{b}	1540.6^{b}	1995.9 ^{b}	0.56 ^{a}	(0.62 ^{a})	0.45 ^{a}	(0.31^{b})	0.50 ^{a}	(0.45 ^{a})
	rainfed	977.8 ^{c}	1512.5 ^{b}	1873.1^{b}	0.55 ^{a}	(0.42 ^{b})	0.50 ^{a}	(0.41 ^{a})	0.48 ^{b}	(0.48^{a})
	mean	**1464.6**	**1754.3**	**2073.6**	**0.57**	**(0.48)**	**0.48**	**(0.37)**	**0.47**	**(0.46)**

^{a,b,c} means within a column followed by the same letters are not significantly different according to Tukey's multiple-comparison test ($P < 0.05$)

Discussion

Growth and development - temporal and spatial differences

Development patterns as well as timing of phenological events differed significantly among the three legumes (Figure 2). Common bean had by far the shortest life cycle, producing grain ready to harvest in less than 80 days. This can be advantageous for cropping with restricted growing periods and soil moisture reservoirs (Muchow et al., 1993; Tesfaye et al. 2006). The development pattern of cowpea was characterized by a comparatively long vegetative phase (~50 days) and a relatively short grain filling period (Figure 2). Consequently, cowpea can benefit more from favorable soil moisture under optimal conditions where, at the same time, high yield losses are recorded if in-season droughts are experienced (Tesfaye et al., 2006; Uarrota 2010). Time to maturity for lablab was comparatively long (<100 days) resulting from long flowering time and a prolonged grain filling period; however, still with potential to return seeds within one season (Whitbread et al., 2011). In general, phenological development shapes the fundamental settings for resource use in time by outlining the development of source and sink plant organs through the definition of vegetative and reproductive growing period lengths (Black and Ong, 2000; Blum, 2005). However, resource capture in space is primarily determined by growth habit, branching pattern and leaf characteristics. Common bean plants are characterized by their fairly small size and compact canopy structure and, as a result, the total leaf area (LAI < 2) remained low compared with the other legumes. In contrast, cowpea has a spreading growth habit, with relatively big plants, reaching an optimal surface coverage (LAI < 5) independent of plant density (Craufurd and Wheeler 1999). This is favorable for great light interception (f almost 100%) under optimal conditions. Furthermore, the dense leaf surface decreases possible water loss through soil evaporation and helps to better conserve soil moisture. However, cowpea leaf appearance and expansion are extremely sensitive to drought (Uarrota, 2010), resulting in a reduced LAI and a decline in intercepted radiation under water limited condition. In summary, the legumes showed distinct differences in growth habit and canopy architecture; corresponding in a distinct ability to intercept PAR (Figure 5) (Huyghe, 1998). However, legume diversity in particular, common bean diversity is known to be among the highest observed for food crops around the world with tremendously high levels of variation in development time and growth habit (Jones, 1999). The differences describes here are therefore rather characteristic for the selected varieties instead of true species differences. The varieties used for analysis are, however, the most recommended and widespread used in semi-arid Eastern Kenya (KARI, 2006).

Resource capture – light interception

The large differences in crop growth and development are also reflected the ability to convert intercepted radiation into dry matter as represented in the differences for the estimated RUE (Figure 8 and Figure 9). The effect of water scarcity during crop growth was conspicuous for common bean and cowpea, where RUE was reduced by almost 70 % and 50 %, respectively. The RUE reported by Tesafaye et al. (2006) were higher, estimating maxima of 2.44 and 2.16 g MJ-1 for common bean and cowpea, respectively.

Even under water stress in Ethiopia, RUE remained relatively high, reaching 1.5 and 1.59, respectively, due to much higher estimated DM accumulation for the varieties used in their study. The current findings, however, support those from Muchow et al. (1993), where RUE for cowpea was determined to be 1.05-1.16 g MJ-1 under non-stressed conditions and 0.64 in a water-limited environment. Also Craufurd and Wheeler (1999) conclude that drought in early stages of cowpea rather affects f than RUE, whereas the opposite is true for drought occurring during the reproductive stage, since leaf senescence is not as sensitive to drought as leaf development. Consequently, cowpea adjusts f through decreased leaf development if drought is experienced in early vegetative stages and through moderated leaf senesce after drought undergone at reproductive development (Craufurd and Wheeler, 1999). This is a rather offensive strategy to regulate source-sink dynamics. Lablab seemed to follow a fairly conservative strategy instead as maximum RUE was lower compared with common bean or cowpea, but no significant reduction in RUE was observed under rainfed conditions, indicating better assimilation efficiency under dry conditions and good adaption to semi-arid environments. Moreover, it was observed that lablab was able to change the leaf angle position with change in sun exposure (paraheliotropism) over the day as an adaption strategy to optimize radiation interception and water loss through transpiration. Pastenes et al. (2004) proved that paraheliotropism can help to minimize water loss and heat stress in common bean, consequently allowing better radiation use under water-limited conditions. These findings are in agreement with the hypothesis by Pengelly et al. (1999), stating that a high RUE can be advantageous under non-water-limiting conditions but may indicate high drought susceptibility and, consequently, high production risk in drier years. On the other hand, low RUE might reflect a conservative agro-morphological plasticity, challenging the crop to respond to superior, favorable conditions in periods of higher rainfall (Black und Ong, 2000; Pengelly et al., 1999). In summary, RUE is one of the key indicators for describing plant development. However, in the legumes studied, plant density and water availability strongly influenced RUE. This inconsistency with management factors or environmental factors should be considered as necessary information to include in plant growth models.

Production potential – environmental constraints

Growth and development of common bean was characterized by a very short flowering and maturity time, relatively low total leaf area due to its rather compact growth habit. This makes common bean suitable for cropping in association with cereal-like crops in intercropping systems for its optimal and less competitive use of light in space and time. The overall reduced biomass production compared with cowpea and lablab, however, reduces the benefit of nutrient cycling through senesced leaves and, thereby, the possible positive impact on soil fertility and overall farm sustainability. In contrast, cowpea seemed to have comparatively long vegetative cycle and a high phenological plasticity affecting total leaf area and light interception with the ability to respond to increased water supply by increased leaf development, spreading growth and maximal soil surface coverage. As a consequence, cowpea responded positively to increased water supply by out-yielding all other legumes under optimal conditions (Table 7). Observed cowpea yields were even higher than those reported by Tesafaye et al. (2006), reaching 1700 kg ha-1 only, even under well-watered conditions and Uarrota

(2010), where only up to 800 kg ha-1 were determined with appropriate P applications (Tesfaye et al., 2006; Uarrota, 2010). The vigorous growth habit and possible competiveness, however would make timing critically important if incorporated in intercropping systems in association with non-legume crops. Nevertheless, cowpea leaves are a highly valued African vegetable (Dube and Fanadzo, 2013) and high leaf productivity is a major feature of cowpea with the potential to add to small-holders' food and nutrition security, health and income.

The HI- a key determinant for potential yield accumulation - did not change significantly with changes in plant density and water regime for both cowpea and common bean, indicating that translocation to reproductive organs is not decreased by dry conditions but rather a function of the accumulated biomass alone. This is in accordance with findings from Muchow et al. (1993) and Craufurd and Wheeler (1999), confirming the conservative nature of biomass partitioning in cowpea. Consequently, grain yield of common bean and cowpea is primarily determined by the ability to accumulate biomass even under dry conditions. Lablab seemed to be the most consistent and robust among the studied legumes with stable RUE, even under water-limited conditions. The comparatively long growing period allowed to buffer environmental shocks leading to fairly stable biomass and yield production. Relatively high yields of lablab even under dry conditions are in agreement with observations by Maundu et al. (1999) and the review by Maass et al. (2010). Moreover, lablab herbage can be used as a quality animal feed, helping to boost milk production if obtained in sufficiently large quantities (Njarui et al., 2004).

Unfortunately, there is not much information of the production potential of short-season grain varieties of lablab in the semi-arid environment of East Africa. Surprisingly, increased planting densities of lablab led to vigorous vegetative growth and significantly increased biomass production but decreased grain yield accumulation, resulting in reduced HI estimates. The same phenomenon was observed on farmers' fields in Machakos, Kenya, where lablab was planted at similar densities like common bean (data not shown). Therefore, plant density can be considered as very important for the production success of lablab as high plant densities lead to vigorous vegetative development and low pod set. Furthermore, selection towards consistently early flowering determinate varieties is important for the production success in the restricted time window of one growing period.

Finally results highlight different species have different production potential, but within their specific genetic endowments, phenological plasticity of legumes is pronounced and ability to respond to changing environmental conditions is very distinctive (Ayaz et al., 2004). High variability in yield and HI was also found in other comparative studies (e.g. Ayaz et al., 2004; Muchow, 1985; Tesfaye et al., 2006; Sinclair and Ludlow, 1986). However, characteristic for all three legumes was the pronounced leaves senescence towards the end of the growing period, leading to comparable high determined HI values if referred to total biomass at maturity (Table 6). Since flowering date directly influences HI, it determines the time shift from vegetative to reproductive growth. However, the short-season varieties, like the ones studied, were bred to reach high HI in short time. Ayaz et al. (2004) report similar high biomass production and HI for the short-season grain legumes chickpea, lentils and pea (HI > 0.5). Certainly, short-season legume varieties, including the legumes studied, are superior in exploiting available resources in

environments where agricultural production is primarily limited by the supply of water (Cooper et al., 2009). Early emergence and fairly short vegetative periods allowed flowering and, most importantly, the setting of pods during the rainy period when soil moisture conditions were most favorable. Thomson and Siddique (1997) observed similar development for grain legumes in low rainfall Mediterranean-type environments. However, the shorter is not necessarily always the better; instead, a good alignment of growth cycle with environmental conditions is important, which allows full or optimal exploitation of available resources with the ability to adapt to environmental changes (Cooper et al., 2008).

Thereby, it seemed that the studied legumes have distinct potential and follow different adaption strategies to cope with short growing periods and restricted water availability. This can be exploited to better identify niches for short-season grain legumes and to design strategies for climate-smart agriculture in the small-scale farming systems of Eastern Kenya.

Conclusion

The temporal and spatial variability in growth and development of common bean, cowpea and lablab represented by variations in dry mater accumulation, LAI, HI and RUE could be used for application in different farming systems with a distinct production orientation, and exploited to help farmers to become more resilient in the view of climate change. Caution is needed, however, to generalize these findings across the species as all three have wide genetic diversity available partly being used by smallholders. Nevertheless, the findings from this study highlight important differences in growth and development of legume species leading to different application possibilities within in the smallholder farming systems. Furthermore, the generated information is particularly valuable for use in crop modelling to advice agronomist and plant breeders about management and genetic options for semi-arid areas.

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III. Simulating the growth and development of short-season grain legumes in semi-arid Eastern Kenya

Introduction

The potential of legumes in smallholder farming systems of Sub-Saharan Africa (SSA), including semi-arid Eastern Kenya is widely acknowledged. The benefits of green manure, grain and fodder legumes for the farmers, farming systems, environment and economy have been reported in many publications (Graham and Vance, 2003). Despite intensive research the application and adoption of legume-associated technologies and the contribution of food, fodder and soil-fertility-improving legumes to smallholder systems has remained far beyond its potential (Ojiem et al., 2006). In semi-arid areas, degraded soils, inadequate and highly variable rainfall and short growing periods limit yield potential and create a risky primary production environment. However, legumes display wide agro-morphological diversity with great potential for adaption to challenging environments. Locally adapted short-season varieties of grain legume species from semi-arid areas such as common bean (*Phaseolus vulgaris* (L.)), cowpea (*Vigna unguiculata* (L.) Walp.) and lablab (*Lablab purpureus* (L.) Sweet) offer new possibilities for farming with increased uncertainties in risk-prone environments, including new management options.

In order to explore the potential of certain crops and cropping strategies in diverse smallholder farming systems and for different environments the development and application of crop growth simulation models has been proved to be an excellent tool (Whitbread et al., 2010). Since African farming systems are highly heterogeneous, simulation models manage to address the complexity of these systems, which is difficult to address through classical agronomic experiments alone (Robertson et al., 2001; Whitbread et al., 2010; Holzworth and Huth, 2009). Simulations models are able to capture interactions between climatic conditions, soil type and nutrient dynamics. One of the most applicable models to better understand the complexities of plant growth in response to the environment has been the Agricultural Production System sIMulator (APSIM) framework (Keating et al., 2003; Holzworth et al., 2014). Some key physiological parameters for legumes have been adjusted for APSIM from the literature already. With the creation of modules to simulate grain and forage legumes such as cowpea (Adiku et al., 1993), soybean (Robertson and Carberry, 1998), pigeonpea (Robertson et al., 2001), mungbean (Robertson et al., 2002) and fababean (Turpin et al., 2002, 2003), and improvements to module design made by Robertson et al. (2002), APSIM has shown to be a powerful tool for designing legume-cereal systems for a changing environment. Despite the imporvements made to better simulate biomass accumulation and grain yield production of legumes, scrutiny of the literature reveals that the accuracy to simulate growth and development of short-season legumes is not yet very sophisticated. This is in particular true for the commonly cultivated grain types of common bean, cowpea and lablab especially risky environments such as the semi-arid areas of Sub-Saharan Africa including Eastern Kenya for instance.

Model validation and testing has focused mainly on Australian production systems where vegetative or forage types of cowpea and lablab are used in grazing systems. Further, the number of cultivar-specific parameters to be changed to parameterize APSIM for new cultivars is restricted und limited to thermal time requirements to reach certain developmental stages, as well as the harvest index (HI), the daily increase in HI and plant height.

However, parameters like the extinction coefficient (k), radiation use efficiency (RUE) and transpiration efficiency (TE) are known to primarily determine plant growth in semi-arid environments (Black and Ong, 2000). Given the difficulty and expense of collecting appropriate and comprehensive physiological data to parameterize them for simulations models, a sensitivity analysis of parameters critical for the crop performance in challenging environments, can be used to estimate their impact on the overall potential of legumes in smallholder farming systems. If calibrated well, crop growth models can function as powerful tools to exploit the potential of different grain legumes in different environments and under various (future) climatic conditions (Keating et al., 2003). This could help to better identify entry points for short-season grain legumes with different potential in existing farming systems of semi-arid Eastern Kenya.

Against this background, the objectives of this study were (i) to quantify essential cultivar-specific parameters to better calibrate APSIM to simulate growth and development of short-season-grain legumes under semi-arid conditions; (ii) to validate the model against field data from Machakos, Eastern Kenya; (iii) to evaluate the impact of species-specific parameters: extinction coefficient (k), radiation use efficiency (RUE) and transpiration efficiency (TE) using a sensitivity analysis; and (iv) to assess overall performance of the legumes to better channel agricultural interventions to find suitable entry points in already exiting maize-based farming systems in Eastern Kenya.

Material and methods

The parameters and relationships necessary to build the functions within the APISM model framework and configure the sub-models (called modules) were derived mainly from field experiments conducted in semi-arid Eastern Kenya, which are described in detail in chapter II.

Experimental studies

Field experiments were designed to derive parameters for short-season legumes and semi-arid conditions not available from published studies. All experiments were conducted at the Kenyan Agricultural Research Institute (KARI), Katumani in semi-arid Eastern Kenya (1º35'S: 37º14'E, 1592 m). The cultivars used in the experiments were short-season grain legume varieties of common bean (cv. KAT X56), cowpea (cv. M66) and lablab (cv. DL1002), representative, most commonly used and recommended cultivars for semi-arid areas in Eastern Kenya. The experiments were conducted during the short rains each of 2012/13 and 2013/14. Sowing was carried out at onset of the rains on the 14th of November in 2012 and on the 5th of November in 2013. Standard

agronomic plant protection measures were followed to control weeds and pests in order to minimize biotic stresses. Triple superphosphate (TSP) was applied at planting at a rate of 20 kg P ha^{-1} as well as nitrogen as Urea at a rate of 10 kg N ha^{-1} to ensure sufficient nutrient supply for successful seedling establishment to ensure satisfactory nutrient supply.

Experiment 1 – Plant density trial

This experiment was designed to provide data on legume phenology as well as biomass and grain yield development in response to plant density. Therefore legumes were sown at three different plant densities; 'medium' following the recommendations by KARI for farming in semi-arid areas (KARI, 2006), while 'high' was double and 'low' only half of the recommended density (Table 1) irrigated throughout the experiment (total of 50 mm of water per week with additional drip irrigation).

Experiment 2 – Water response trial

The water response trial aimed to provide data on biomass development and partitioning as well as soil moisture dynamics in respect to water availability. All three short-season grain legumes were grown under optimal (´medium`) plant density with three water treatments; purely rainfed, partly irrigated (total 50 mm of water per week with additional drip irrigation till bud formation, i.e., onset of flowers), fully irrigated (total of 50 mm of water per week with additional drip irrigation throughout the growing period) (Table 1).

Data collection

Weather

Meteorological data including rainfall as well as minimum and maximum temperatures were recorded on daily basis in the field. Solar radiation records were obtained from the meteorological station at KARI Katumani, Machakos, Kenya. In the treatment where irrigation was carried out, the amount of water was recorded.

Soil

The trials were located on fairly well-drained reddish brown chromic Luvisols with a clay texture throughout the profile but an increased sand content at the surface layer. The soil was slightly acid to neutral with a pH ranging from 5.5 to 7, and fairly poor in plant nutrients such as nitrogen, phosphorus, calcium, and zinc and with a relatively low organic matter content (OC ≤ 1 %). Prior to sowing, pH, soil texture (hydrometer method) and soil fertility status were analyzed. A total of 10 samples per layer (0-15, 15-30, 30-60 and 60-90 cm) were randomly taken across the experimental site for analysis at the KARI National Agricultural Research Laboratories (NARL) in Nairobi, Kenya. Furthermore soil moisture was monitored throughout the growing period for the water response trial and determined gravimetrically depth-wise for the top four layers (at 0-15, 15-30, 30-60, 60-90 cm). The volumetric soil water content was calculated by multiplying gravimetric water content at a given depth interval with BD at the corresponding depth.

Table 1: Summary description of the treatments showing the plant density and water response trial at KARI Katumani, Machakos, Kenya during the short rains of 2012/13 and 2013/14.

Season	Species	Treatment plant density	Treatment water regime	Treatment ID	Plant density [plants m^{-2}]	Irrigation [mm]	In-crop rainfall [mm]	Irrigation + rainfall [mm]
2012/13	Bean	medium	*rainfed*	rm	10	0	156	156
		medium	*partly irrigated*	pm	10	150	156	306
		medium	*fully irrigated*	fm	10	270	156	426
		low	fully irrigated	fl	5	270	156	426
		high	fully irrigated	fh	20	270	156	426
	Cowpea	medium	*rainfed*	rm	10	0	190	190
		medium	*partly irrigated*	pm	10	225	190	415
		medium	*fully irrigated*	fm	10	300	190	490
		low	*fully irrigated*	fl	5	300	190	490
		high	*fully irrigated*	fh	20	300	190	490
	Lablab	medium	*rainfed*	rm	4.17	0	190	190
		medium	*partly irrigated*	pm	4.17	210	190	400
		medium	*fully irrigated*	fm	4.17	345	190	535
		low	fully irrigated	fl	2.08	345	190	535
		high	fully irrigated	fh	8.33	345	190	535
2013/14	Bean	medium	*rainfed*	rm	10	0	259	259
		medium	*partly irrigated*	pm	10	60	259	319
		medium	*fully irrigated*	fm	10	240	259	499
		low	fully irrigated	fl	5	240	259	499
		high	fully irrigated	fh	20	240	259	499
	Cowpea	medium	*rainfed*	rm	10	0	259	259
		medium	*partly irrigated*	pm	10	180	259	439
		medium	*fully irrigated*	fm	10	330	259	589
		low	*fully irrigated*	fl	5	330	259	589
		high	*fully irrigated*	fh	20	330	259	589
	Lablab	medium	*rainfed*	rm	6.7	0	339	339
		medium	*partly irrigated*	pm	6.7	180	339	519
		medium	*fully irrigated*	fm	6.7	345	339	684
		low	fully irrigated	fl	3.3	345	339	684
		high	fully irrigated	fh	13.3	345	339	684

Plant

The data collected included time to flowering and physiological maturity in days after planting (DAP), LAI, biomass of the whole plant and plant parts (leaves, stem, pod, podwall and grain) and grain yield. The LAI was measured every week while the biomass yields were sampled every 2 weeks after plant establishment as well as the grain yield at physiological maturity.

Model description

APSIM is a widely used farming system model that simulates crop growth and development upon incoming radiation limited by temperature stress, water supply and N availability (Holzworth et al., 2014). Management decisions such as sowing date or plant density, etc. can be specified in a manager module. Accordingly, APSIM (version 7.5r3008) was configured with the modules for common bean (navy bean), cowpea and lablab as well as soil water (SOILWAT), soil N (SOILN) and the manager.

Parameterization of the APSIM model

The APSIM model was parameterized for short-season varieties of common bean (navy bean), cowpea and lablab grown at optimal condition (medium density, fully irrigated) without biotic stresses during the short rains of 2012/13 in field experiments conducted at KARI Katumani, Kenya.

Weather conditions

The APISM met file was created from daily measurements of minimum, maximum temperature, rainfall and solar radiation within the KARI Katumani research station (Figure 1). Further additional irrigation was recorded on daily basis (Figure 1).

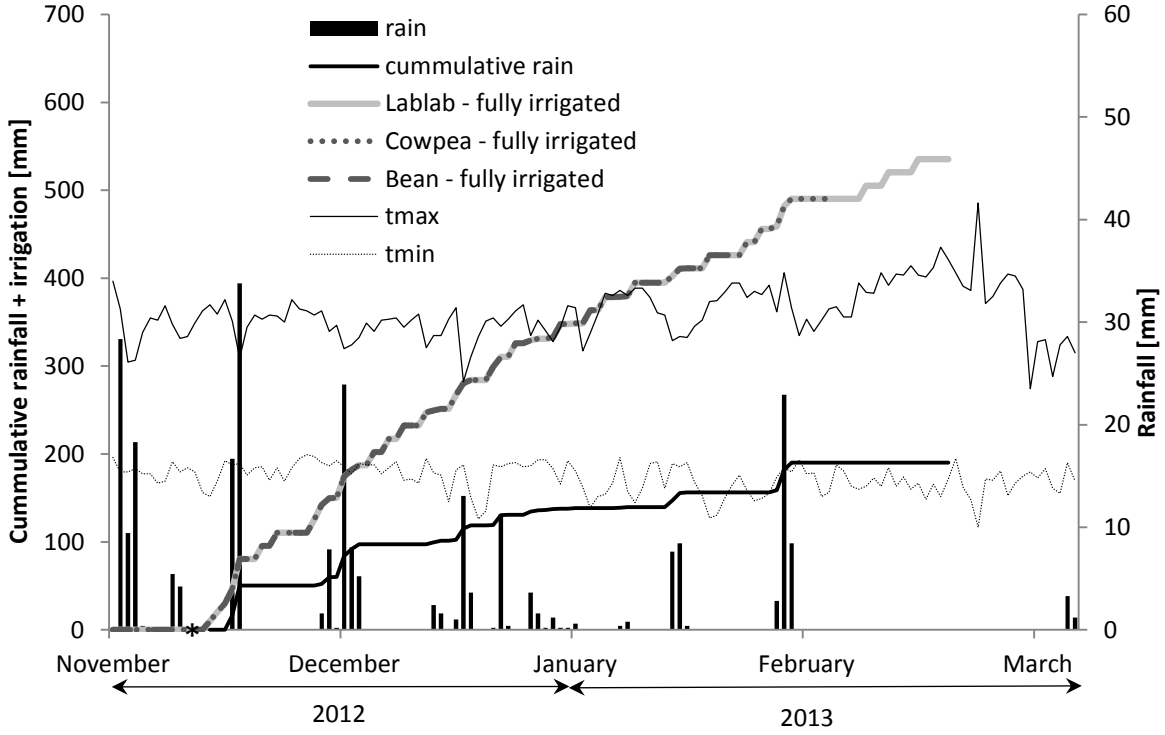

Figure 1: Daily minimum and maximum temperatures, rainfall and cumulative rainfall and irrigation for three different legumes (common bean, cowpea and lablab) during the short rains of 2012/13 at KARI Katumani, Kenya.
*planting date

Soil parameterization

The SOILWAT and SOILN modules were parameterized following standard practices using APSIM. Necessary parameters were estimated from prior soil characterization data by Gicheru and Ita (1987) and measured data from the above described field experiments for the study site at the KARI Katumani, research station in Machakos.

The two parameters that determine first (U) and second stage (Cona) of soil evaporation were set to 4 and 2 mm day^{-1}, respectively. Runoff is linked to the setting of the USDA curve number, in this case 73. The fraction of water drained to the next soil layer under saturated conditions per day (SWCON) was set to 0.7 for the more sandy top layer (0-15 and 15-30 cm), to 0.5 for the loamy middle layer (30-120 cm) and to 0.3 at depth > 120 cm with high clay contents. For soil water content below drained upper limit (DUL), water movement depends upon the water content gradient between adjacent layers and the soil's diffusivity, defined in APSIM as diffusivity constant and diffusivity slope. Standard default values of 250 (diffusivity constant) and 22 (diffusivity slope) were used to represent a sandy loam soil.

To define the plant available water content (PAWC) of each zone within SOILWAT a number of soil variables were measured on-site including bulk density (BD), AirDry, DUL and estimated such as Saturation (SAT) (Table 2). SAT gives the total porosity (PO) and was calculated from BD (Eq. (1) and (2)) (Dalgleish and Foale, 1998).

$$PO = 1 - BD/2.65 \qquad (1)$$

$$SAT = PO - 0.03 \qquad (2)$$

DUL was measured at five points at the experimental sites using the procedure described by Dalgliesh and Foale (1998). The site-specific crop lower limit (CLL) for each legume species was determined during the implementation of the experiment using the lowest soil moisture values above a tent measured at harvest (Rattliff et al., 1983). The root hospitality (XF) was set according to specific rooting characteristics and sub-soil constraints separately for each legume species; for common bean, XF was limited to a depth of 100 cm, for cowpea 120 cm and lablab 150 cm.

Table 2: Layer soil type parameters used by the APSIM-SOILWAT module: bulk density (BD) ,soil water content at air dry (AIR_DRY), 1.5 MPa tension (LL15), the drained upper limit (DUL) and saturation (SAT), as well as the species-specific crop lower limit (CLL) and root hospitality factors (XF) at the experimental site KARI Katumani, Kenya.

Parameter	Depth (cm)						
	0-15	15-30	30-60	60-90	90-120	120-150	150-180
BD (g cm^{-3})	1.57	1.57	1.54	1.50	1.51	1.51	1.51
AIR_DRY [a] (cm cm^{-1})	0.020	0.052	0.085	0.099	0.099	0.099	0.099
LL15 [a] (cm cm^{-1})	0.039	0.072	0.085	0.099	0.099	0.099	0.099
DUL (cm cm^{-1})	0.190	0.210	0.300	0.350	0.350	0.350	0.350
SAT (cm cm^{-1})	0.378	0.378	0.389	0.404	0.400	0.400	0.400
CLL (cm cm^{-1})							
bean	0.039	0.072	0.122	0.138	0.138	0.138	0.138
cowpea	0.039	0.072	0.085	0.099	0.099	0.099	0.099
lablab	0.039	0.072	0.100	0.110	0.120	0.120	0.120

[a] adapted from Gicheru and Ita (1987) similar to APSIM soil file: ´Chromic Luvisol, Katumani Research Station` from the international APSIM soil file database for Kenya.

Soil orgaic carbon (OC), initial soil mineral nitrogen (N) content and water content were measured prior to sowing. OC content (%) in the soil was measured for the top layers and was assumed to decrease exponentially with depth (0-15 cm: 0.9, 15-30 cm: 0.8, 30-60 cm: 1.0, 60-90 cm: 0.7, 90-120 cm: 0.6, 120-180 cm: 0.49). FINERT and FBIOM, the different pools of the organic matter are defined according to typical default values representing the fraction of the total organic carbon in the specific pool (FBIOM: 0-15 cm: 0.035, 15-30 cm: 0.020, 30-60 cm: 0.015, 60-180 cm: 0.010; FINERT: 0-15 cm: 0.390, 15-30 cm: 0.470, 30-60 cm: 0.520, 60-90 cm: 0.620, 90-120 cm: 0.740, 120-150 cm: 0.830, 150-180 cm: 0.930) (Luo et al., 2014). The Initial N content (%) in the soil was based on the on-site measurements of total N content prior to sowing (NO_3 in kg ha^{-1}: 0-15 cm: 13.44, 15-30 cm: 9.525, 30-60 cm: 10.050, 60-180 cm: 3.93; NH_3 in kg ha^{-1}: 0-15 cm: 1.920, 15-30 cm: 0.191, 30-60 cm: 0.402, 60-180 cm: 0.399). Initial water content at sowing was adjusted according to the soil moisture measurements and set to 20 % filled from the top.

Parameterization of the short-season legume varieties

From the experimental measurements, cultivar-specific parameters required to simulate growth and development of common bean, cowpea and lablab with APSIM were determined (Table 3). Thermal time (T_t, °Cd) requirements to reach specific phenological stages were computed applying the algorithms used in CERES-Maize on the basis of daily inputs of maximum and minimum temperatures (Jones and Kiniry, 1986). Base, optimal and maximal temperatures (T_b, $T_{optimal}$, T_{max}, °C) were assumed to be 9, 25 and 37 °C, respectively, for common bean, 10, 34 and 44 °C, respectively, for cowpea and 10, 30 and 40 °C respectively for lablab (Hill et al., 2006; Robertson et al., 2002; Turpin et al., 2003). The HI was parameterized with the HI at harvest as implemented by the APSIM plant module, representing the grain yield in relation to the total above-ground biomass at maturity. The potential decrease in HI was estimated from the HI and the time needed from the start of grain filling till maturity. Characteristic for the studied short-season legumes was a pronounced leaf senescence towards the end of the growing period, at maturity almost all leaves were dropped. Therefore, the fractions of senesced leaves detached from the plant were set to 100 % to ensure exact HI estimates.

Because previous lablab model calibration work was restricted to vegetative and perennial types, further adjustments of the species-specific parameters were necessary in addition to the cultivar-specific parameters to simulate growth and development of a grain-type annual short-season variety. Therefore, the leaf number development rate was adjusted according to the observed measurements, and the node appearance rate was set to 90 °Cd.

Further, the leaf number development was adjusted to account for comparatively slow biomass accumulation at early stages but high potential during later developmental stages to better describe the restricted vegetative growth and a rather compact growth habit. Additionally, the translocation characteristics were adapted and the structural proportion of stem and leaf plant parts was lowered to 50 and 70 %, respectively, to enable the crop to achieve proportional yields with the accumulated biomass accounting for relatively high HI values observed for the studied short-season lablab variety.

Table 3: Cultivar-specific APSIM parameters for different short-season grain legume species common bean, cowpea and lablab.

APSIM parameter description	Units	Legumes species		
		Bean	Cowpea	Lablab
Daily potential increase in HI	/day	0.019	0.036	0.017
Maximum HI		0.52	0.54	0.53
Thermal time requirements from:				
sowing to emergence	°Cd	100	50	70
emergence to end of juvenile	°Cd	235	580	500
end of juvenile to floral initiation	°Cd	50	90	100
floral initiation to flowering	°Cd	40	20	20
flowering to start grain fill	°Cd	50	70	50
start grain fill to end grain fill	°Cd	240	250	300
end grain fill to maturity	°Cd	60	20	100
maturity to harvest ripe	°Cd	5	5	5

Validation of the APSIM model

The calibrated APSIM model was validated to simulate soil water content, phenology, biomass and yield accumulation of common bean, cowpea and lablab against the experimental data from the plant density and water response trials. The aim was to evaluate the effect of plant population and water deficit on growth and development of short-season grain legumes in semi-arid areas.

Therefore, weather files were set according to daily measurements of minimum and maximum temperatures as well as daily rainfall and irrigation as recorded during the field experiments. Parameterized soil files from the parameterization procedure described under 2.1.1 were used for model validation. Soil moisture contents were adjusted according to the specific conditions.

Statistical analysis

The model evaluation was performed on the five treatments and the two years of data on the plant density and water response experiment for flowering and maturity dates as well as soil moisture content of the soil profile, biomass accumulation and grain yield. Measured and predicted data were compared graphically and analyzed statistically (Loague and Green, 1991). The statistical criteria are based on the analysis of residual errors, i.e., the difference between observed and simulated values. The root mean square error (RMSE) and the modelling efficiency (EF) were computed (Smith et al., 1996), (Eq. (3) and Eq. (4)) as follows:

$$RMSE = \sqrt{\sum_{i=1}^{i=n} \frac{(P_i - O_i)^2}{n}} \qquad (3)$$

$$EF = 1 - \left[\frac{\sum_{i=1}^{i=n}(P_i - O_i)^2}{\sum_{i=1}^{i=n}(O_i - \bar{O})^2}\right] \qquad (4)$$

Root mean square error (RMSE) with P_i, predicted value, O_i, observed value, $\bar{O}$, mean of the observed values and n, number of observation. For good model performance, values of RMSE should be close to 0; high values of RMSE indicate poor model performance. The EF compares the deviations between predicted and observed values to the variance of the observed values. EF values range from -∞ to 1.0, with higher values indicating better agreement between model simulations and observations. An EF value of 1 denotes a perfect match of predicted and measured values. A value of zero indicates that the model performance is as good as the mean observed value of treatments. RMSE and EF were calculated for biomass and grain yield. Additionally, for comparison, the traditional R^2 regression statistic (least-squares coefficient of determination) was determined.

Sensitivity analysis of the APSIM legume modules

The sensitivity of simulated biomass and yield of common bean, cowpea and lablab was tested for key growth parameters of the corresponding legume modules. Parameters were selected according their agronomic and physiological significance for cropping in semi-arid and their potential importance in terms of biomass and yield accumulation. Some parameters were determined from the field trial data as described in chapter II for the same short-season legumes i.e. the RUE. The extinction coefficient was determined as quasi independent variable from the same dataset represented in chapßer II. For the sensitivity analysis determined values from chapter II were included. Others were selected according to the degree of uncertainty in their values due to lack of experimental information for short-season legume varieties in semi-arid areas such as the transpiration eefficiency (TE).

Table 4: Parameters of the APSIM legume module used in the sensitivity analyses.

Parameter	Description	Species	Default value	Perturbed value		
				Measured	Minus 20 %	Plus 20 %
k	extinction coefficient	Bean	0.70 [a]	0.71	0.56	0.84
		Cowpea	0.55 [a]	0.78	0.44	0.66
		Lablab	0.60 [a]	0.70	0.48	0.72
RUE	radiation use efficiency	Bean	1.4 [b]	1.4	1.1	1.7
		Cowpea	1.1 [b]	1.0	0.9	1.3
		Lablab	1.0 [b]	0.9	0.8	1.2
TE	transpiration efficiency	Bean	0.45 [b]		0.4	0.5
		Cowpea	0.50 [b]		0.4	0.6
		Lablab	0.50 [b]		0.4	0.6

[a] at a row spacing of 20 cm
[b] before start of grain filling

First, the model goodness was revised with the perturbed values used for the sensitivity analyses (Table 4). Secondly, sensitivity analyses were carried out by conducting a long-term simulation (1981-2014) at Machakos, Kenya using similar soil parameterization to evaluate the impact of the selected parameters on actual biomass and yield development under semi-arid conditions.

In the simulations, legumes were grown under recommended densities (medium density, Table 1) and rainfed conditions. Sowing was realized at the onset of the short rain season after three consecutive days of rain.

Soil nitrogen and soil water was reinitialized before the start of the short rains every year at the first of October to eliminate long-term changes in soil fertility and soil water moisture. Residues were removed from the field as observed on famer's fields in the study area.

Simulation experiment

The aim of the simulation experiment was to estimate the yield potential of the short-season legumes under rainfed condition in semi-arid Eastern Kenya and to evaluate the impact of sowing date and plant density on biomass accumulation and grain yield development. Therefore, a long-term simulation with historical climate data from 1981 to 2014 was set up for common bean, cowpea and lablab with the calibrated short-season varieties. Three plant densities were tested in the simulation, medium density following the recommendations for row and inter-row spacing by KARI for farming in semi-arid areas, low density and high density (Table 1). Further, two sowing windows were included in the simulation, early sowing (dry sowing) before the actual onset of the rains before the end of October and late sowing after the onset of the rains (3 consecutive days with at least 20 mm of rain) in November. The simulations were initialized to simulate legume growth and development during the short rain season from October to March.

The soil parameterization was set similar to the previous simulations and representative for soil water and nitrogen characteristics of a sandy loam soil in the research area (Table 2). Soil water was set to 20 % filled from the top in the starting year and later reset to 0 % at the first of October as usually observed after the long dry period to create comparable initial soil water conditions in each growing period. Fertilizer was not applied to account for farmer's practice of legume cultivation in smallholder farming systems. Nitrogen was reset to initial values prior to sowing in each season to exclude the bias of varying nitrogen content in the soil on biomass and yield accumulation. About 90 % of the legume residues were removed from the field as observed on farmers` fields in the study area. Tillage was realized at the first of October before the start of the rain season.

Results

Parameterization of the APSIM – legume modules

After calibration of the cultivar-specific (and species-specific for lablab) parameters for the short-season grain legumes good agreement was obtained between predicted and observed values for the phenological development (Table 5), biomass accumulation (Figure 2) and grain yield development (Table 5).

Phenology

From the datasets estimated thermal time measures represented the short-season characteristics of the studied legumes very well. The error in prediction of days to flowering and physiological maturity for all three legumes was within one day (Table 5). Common bean flowered within 35 DAP, whereas cowpea and lablab needed 58 and 62 days, respectively. Time to physiological maturity was shortest for common bean (71 DAP) and longest for lablab taking 98 days.

Table 5: Observed and simulated (APSIM) time to flowering and physiological maturity in days after planting (DAP) for short-season varieties of common bean, cowpea and lablab.

Species	50 % flowering [DAP]		Physiological maturity [DAP]		Grain yield [kg]	
	observed	simulated	observed	simulated	observed	simulated
Bean	35	35	71	72	1888.2	1776.1
Cowpea	58	57	85	86	3060.6	2957.1
Lablab	62	61	98	98	1932.6	1961.0

Biomass and grain yield

Biomass and grain yield accumulation was fast but lowest for common bean. The measured grain yield at harvest observed for common bean was 1.86 t ha^{-1} compared with the simulated grain yield of 1.79 t ha^{-1}. Total biomass at maturity was 3.63 t ha^{-1} compared with the predicted yield of 3.42 t ha^{-1} (Figure 2). Similar good fit was observed for cowpea, with the final measured biomass (5.63 t ha^{-1}) and grain yield (3.06 t ha^{-1}) being higher than the simulated biomass and grain yield of 5.86 t ha^{-1} and 2.96 t ha^{-1} respectively (Figure 2). The biomass and grain yield accumulation of lablab was slowest and lower than for cowpea but higher than that of common bean. The measured biomass of lablab at maturity reached 3.65 t ha^{-1} and grain yield 1.93 t ha^{-1}, while the simulated biomass was 3.73 t ha^{-1} and grain yield 1.96 t ha^{-1} (Figure 2).

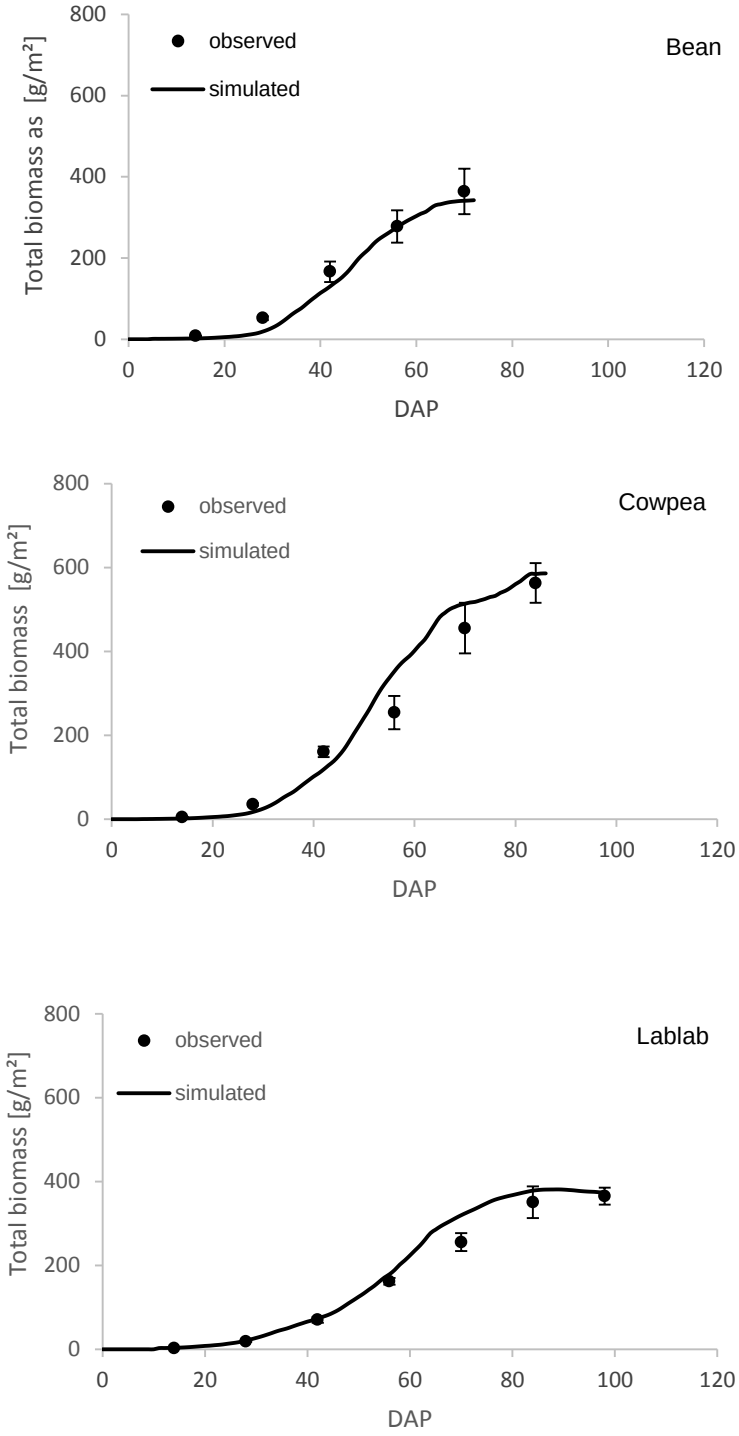

Figure 2: Parameterization of the APSIM model for common bean cowpea and lablab showing observed and predicted values for total above-ground biomass. Vertical bars represent standard deviation from observed data. DAP: days after planting.

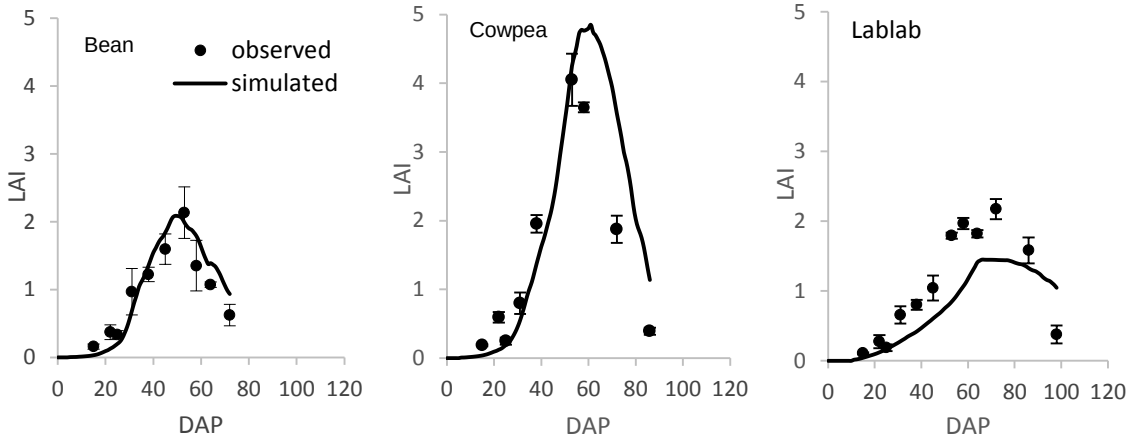

Figure 3: Parameterization of the APSIM model for common bean (cowpea and lablab showing observed and predicted values for leaf area index (LAI). Vertical bars represent standard deviation from observed data. DAP: days after planting.

The development of the LAI over the growing period was very well simulated for common bean (Figure 3). The maximum LAI at flowering for cowpea was slightly overestimated by the model and simulated values reached 5.2 while the measured was 4.1. The opposite was observed for lablab, where the simulation under estimated the LAI development compared with the measured values.

In summary, the measured and simulated LAI, biomass and grain yield were comparable. Therefore, the APSIM legume modules were able to simulate the observed days to 50 % flowering, physiological maturity, LAI, total biomass and grain yield for short-season varieties of common bean, cowpea and lablab reasonable well for semi-arid conditions.

Model validation

The model was validated for soil moisture under rainfed conditions, phenology including observations of flowering time and time to physiological maturity as well as biomass and grain yield.

Soil water balance

The model was validated for changes in soil moisture in the profile under rainfed conditions for common bean, cowpea and lablab using the data collected from the water response trial during the short rain season of 2013/14.

Figure 4 summarizes the change of soil moisture in the profile over the growing period and shows the change of plant available water from the top layer to 90 cm for the three different legumes. The overall changes in soil moisture were represented well by the model simulations but comparatively high standard deviations of the observed data indicate a high degree of variability within the soil.

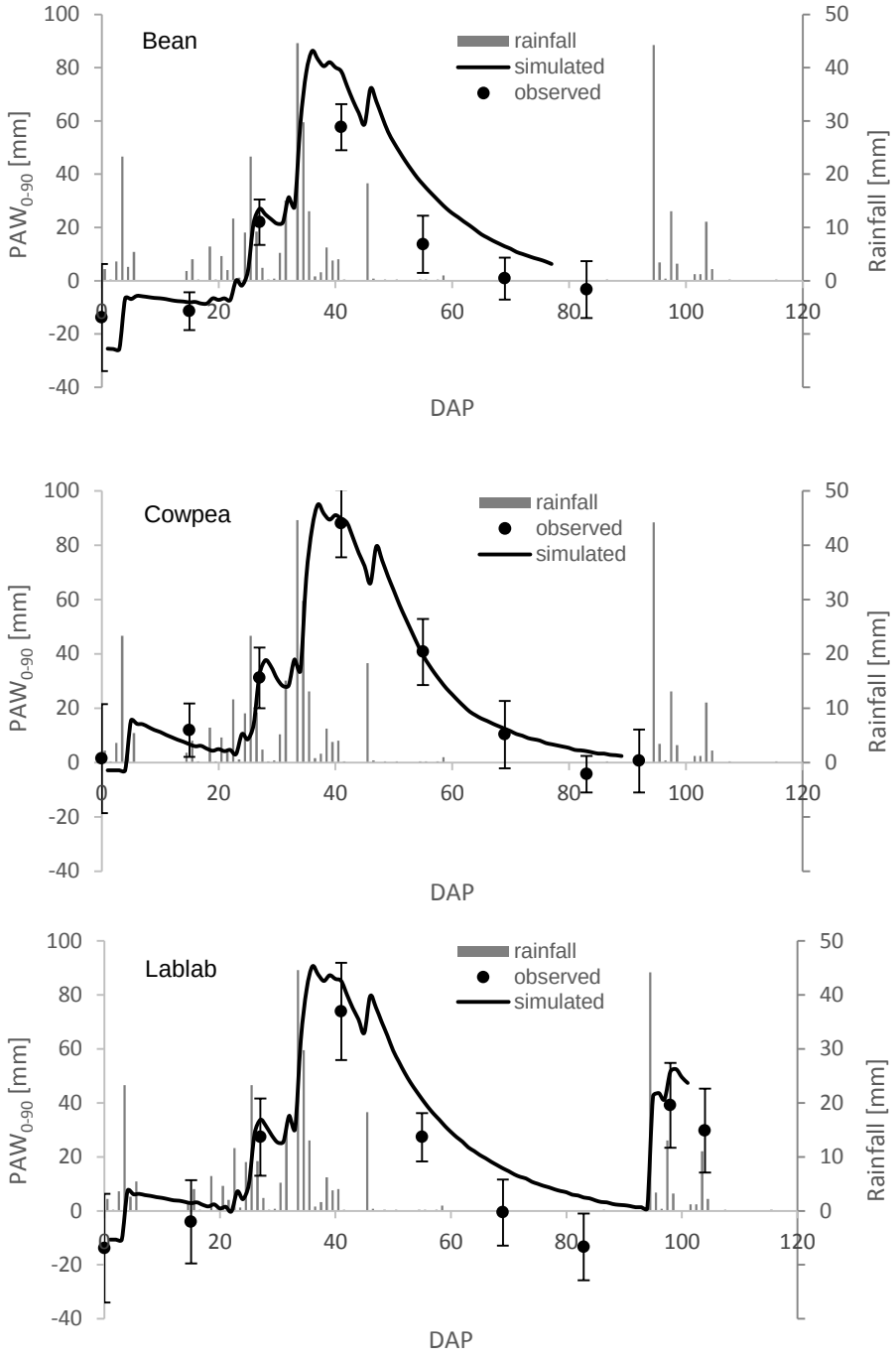

Figure 4: Observed and simulated plant available water (PAW in mm) in the soil profile (0 – 90 cm) over the growing period for common bean, cowpea and lablab planted at medium density under rainfed conditions during the short rains of 2013/14. DAP: days after planting. PAW: plant available water.

The rainfall events are represented very well in the soil moisture simulations and the plant available water increased with the proceeding rain season. A long dry spell occurring from January (49 DAP) led to a fast decline in the soil moisture from 50 DAP onwards and a decrease of the soil moisture below the CLL towards the end of the growing period from 80 DAP onwards. During heavy rainfall, from late November to mid-December 2014, the soil moisture raised above DUL in the top layers. Similar soil moisture dynamics were observed for all three legumes depending on their specific CLL. The model prediction of the volumetric water content during the growing period was relatively accurate (Figure 5) and the rainfall events as well as dry spells were quite visible. The overall soil moisture dynamics were represented fairly well by the soil module parameterization.

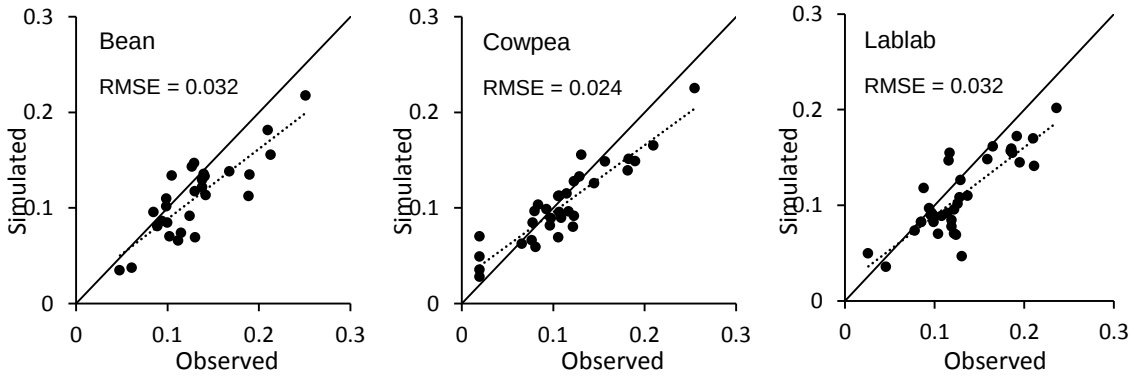

Figure 5: Observed and simulated soil water contents (volumetric water content in mm/mm) at different soil layers for common bean, cowpea and lablab planted at medium density at rainfed conditions during the short rains of 2013/14.

Phenology

In general, there was excellent agreement between observed and simulated days to flowering and days to physiological maturity, with RMSD values being equal or less than 2 days for the time of 50 % flowering as well as time to physiological maturity for lablab (Table 6). The RMSE for the predicted time to maturity for common bean (3.6) and cowpea (5.0) was higher than for lablab (2.1). Time to maturity was simulated with less accuracy than flowering for all legumes, possibly reflecting the additive effects of errors simulating the intermediate flowering and grain fill stages. In general, the model was able to represent the short-season characteristics of the studied legumes well.

Table 6: Statistical criteria (root mean square error, RMSE) and observed range and mean for evaluating the phenological development (time to 50 % flowering and physiological maturity) of short-season varieties of common bean, cowpea and lablab.

Species	Time to…	Unit	RMSE		Observed range	Observed mean	N
			Absolute value	% of mean observed			
Bean	50 % flowering	DAP	1.4	3.9	35-38	36.5	10
	physiological maturity	DAP	3.6	4.8	71-79	75.0	10
Cowpea	50 % flowering	DAP	1.0	1.7	57-58	59.5	10
	physiological maturity	DAP	5.0	5.6	85-89	89.5	10
Lablab	50 % flowering	DAP	1.6	2.5	62-64	63	10
	physiological maturity	DAP	2.1	2.1	98-102	100	10

Biomass and yield

The accuracy of the model in predicting biomass and grain yield at different plant densities and irrigation levels was good for common bean, but fair for cowpea and lablab. However, the observed range of biomass and grain yield was narrower for bean than for cowpea and lablab (Table 7). Therefore, the RMSE was higher for cowpea biomass (916 kg ha^{-1}) and grain yield (509 kg ha^{-1}) leading to lower model efficiency in comparison to common bean. For common bean the RMSE in % of the observed mean was 12.4 for biomass and 11.9 for grain yield predictions and with an excellent EF. Whereas RMSE in % of the observed mean was 23.5 and 26.0 and 20.8 and 25.1 for cowpea and lablab biomass and yield, respectively. This showed that the APSIM model predictions of biomass and grain yield for bean was consistently better than that for cowpea and lablab, represented in the respective model efficiency.

Table 7: Statistical criteria (root mean square error, RMSE and model efficiency, EF) as well as observed range and mean for evaluating total biomass and grain yield of common bean, cowpea and lablab.

Species		Unit	RMSE		Observed range	Observed mean	EF	N
			Absolute value	% of mean observed				
Bean	Total biomass	kg ha^{-1}	370.2	12.4	1762-3741	2975.7	0.64	10
	Grain yield	kg ha^{-1}	191.9	11.9	977-1956	1610.7	0.65	10
Cowpea	Total biomass	kg ha^{-1}	915.7	23.5	2574-5629	3902.9	0.18	10
	Grain yield	kg ha^{-1}	508.7	26.0	1384-3061	1956.7	0.18	10
Lablab	Total biomass	kg ha^{-1}	791.7	20.8	2546-5474	3810.8	0.08	10
	Grain yield	kg ha^{-1}	436.9	25.1	1234-2352	1740.7	-0.47	10

Treatments had significant influence on the development of biomass and grain yield. Biomass and grain yield of all legumes was lowest under rainfed conditions (Figure 6 and Figure 7). APSIM overestimated biomass and grain yield of cowpea and lablab at high densities. For lablab it was observed that high plant densities led to vigorous vegetative growth with very low pod set development and proportional low grain yield, which was not reflected well by the model leading to fairly high deviations in biomass and yield estimation for cowpea and lablab at high plant densities. The response of biomass and yield accumulation to different water regimes was simulated reasonably well by the model for all legumes. The response to different irrigation levels was realistically predicted by APSIM in particular for the fully and partly irrigated treatments indicating a reasonable agreement for these diverse treatments. For cowpea biomass and grain yield at rainfed conditions was underestimated by APSIM. In general the studied short-season varieties showed a good drought resistance, which is not reflected well enough by the model capability.

Sensitivity analysis

The sensitivity analysis revealed that k, RUE and TE had different influence on biomass and grain yield development of common bean, cowpea and lablab. The impact was determined by other indicators, primarily phenological, morphological and physiological characteristics of the different legume species such as growing period length and canopy architecture. The measured values of k and RUE had relatively little influence on the development of the legumes, because of the minor variation in comparison to the standard values implemented in the respective APSIM legume module. The largest impact on biomass and grain yields of common bean was observed for RUE. A reduction of RUE by 20 % changed common bean biomass and grain yield by about -15 %, whereas changes in TE, had comparatively little effect (Table 8). The opposite was observed for cowpea, where changes in k and RUE had very little impact on biomass and grain yield. However, reduction in TE of 20 % led to a decrease in biomass and grain yield of -26 and -21.4 %, respectively, and a 20 % increase to a boost of 16.7 and 14.1 %, respectively. For lablab the response varied for the different parameters. Both the reduction and increase of k and TE had similar effects on lablab biomass and grain yield accumulation. The highest impact was observed for the increase of RUE by 20 % causing a biomass surplus of 15.4 and a grain yield increase of 14.9 % in comparison to the standard.

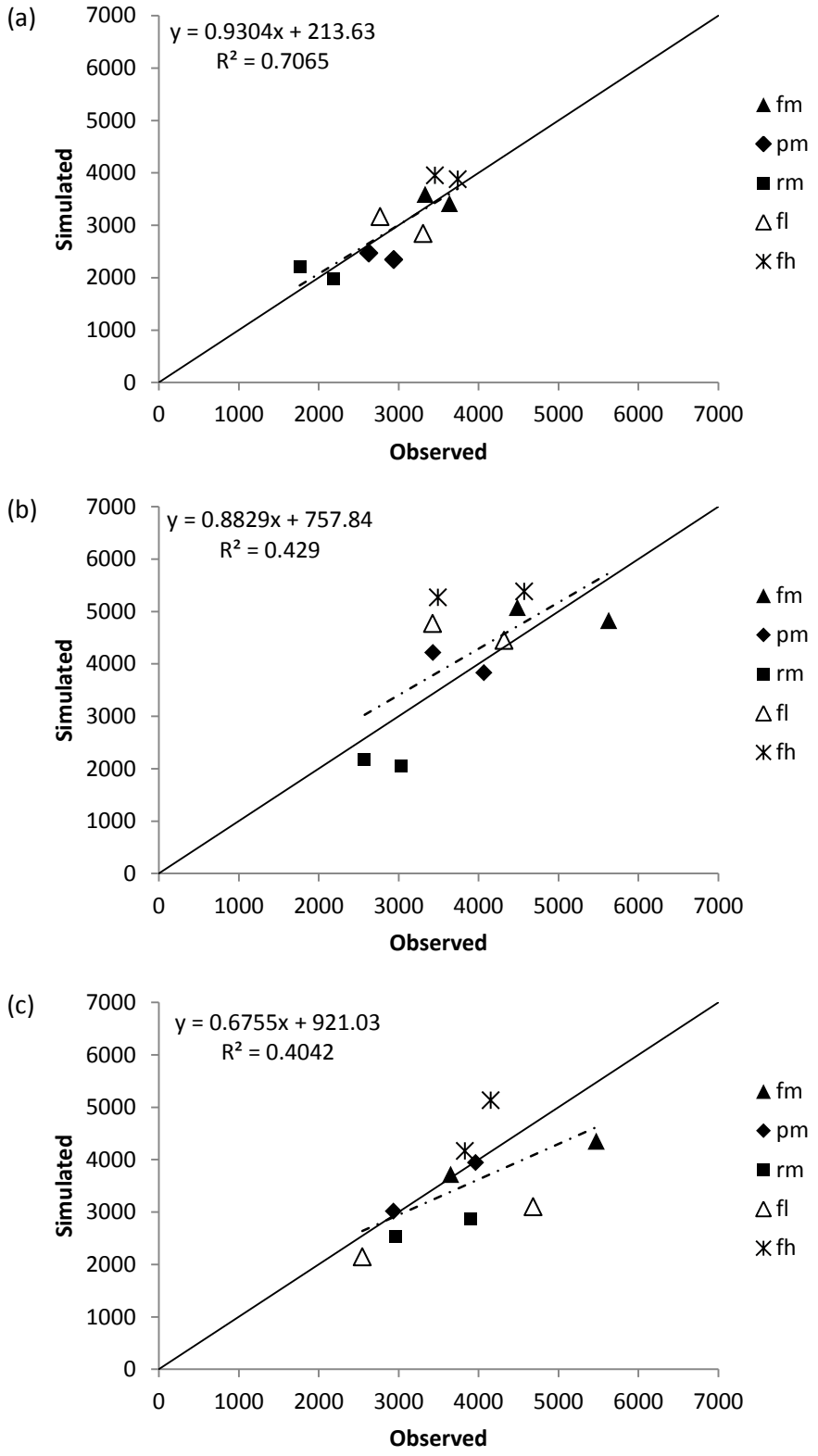

Figure 6: Observed vs. simulated biomass in kg ha^{-1} for (a) common bean, (b) cowpea and (c) lablab for different plant density and water regime treatment combinations (fm: fully irrigated, medium density; pm: partly irrigated, medium density; rm: rainfed, medium density; fl: fully irrigated, low density; fh: fully irrigated, high density).

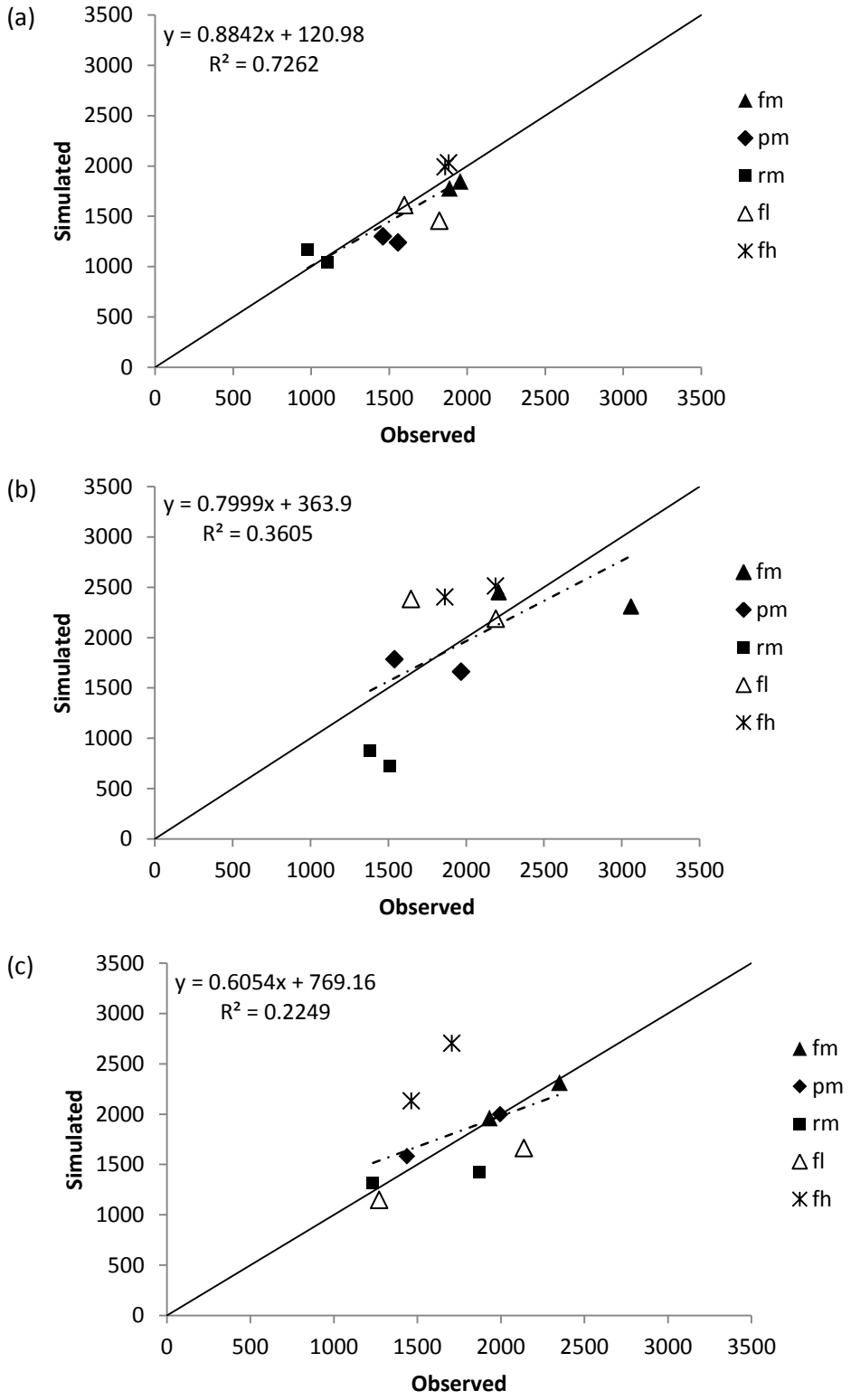

Figure 7: Observed vs. simulated grain yield in kg ha^{-1} for (a) common bean, (b) cowpea and (c) lablab for different plant density and water regime treatment combinations (fm: fully irrigated, medium density; pm: partly irrigated, medium density; rm: rainfed, medium density; fl: fully irrigated, low density; fh: fully irrigated, high density).

Table 8: Results of the sensitivity analysis, were extinction coefficient (k), radiation use efficiency (RUE) in g MJ^{-1} PAR and transpiration efficiency (TE) were perturbed from their standard values by – or + 20 % and measured values for k and RUE were used in a long-term (1981-2014) simulation under semi-arid conditions of Machakos, Eastern Kenya.

Species	Parameter [a]	Specification	Total biomass [kg ha^{-1}]	% change compared to standard	Grain yield [kg ha^{-1}]	% change compared to standard
Bean		standard	1526		2945	
	k	measured	1537	0.7	2967	0.7
		minus 20	1414	-7.9	2714	-8.5
		plus 20	1633	6.5	3162	6.8
	RUE	measured	1526	0.0	2945	0.0
		minus 20	1329	-14.9	2551	-15.4
		plus 20	1713	10.9	3326	11.4
	TE	minus 20	1438	-6.1	2778	-6.0
		plus 20	1601	4.6	3087	4.6
Cowpea		standard	1587		4210	
	k	measured	1613	1.6	4548	7.4
		minus 20	1572	-1.0	3974	-5.9
		plus 20	1598	0.7	4388	4.0
	RUE	measured	1589	0.1	4061	-3.7
		minus 20	1569	-1.2	3868	-8.8
		plus 20	1574	-0.8	4446	5.3
	TE	minus 20	1259	-26.0	3468	-21.4
		plus 20	1904	16.7	4901	14.1
Lablab		standard	1761		3388	
	k	measured	1883	6.5	3628	6.6
		minus 20	1562	-12.8	3009	-12.6
		plus 20	1905	7.6	3671	7.7
	RUE	measured	1832	3.9	3470	2.4
		minus 20	1723	-2.2	3253	-4.1
		plus 20	2082	15.4	3981	14.9
	TE	minus 20	1559	-13.0	3021	-12.1
		plus 20	1895	7.0	3634	6.8

[a] see Table 4 for a description of the parameters

Simulation experiment

The simulation experiment demonstrated the impact of basic management interventions such as sowing date and plant density on phenological development and biomass and grain yield accumulation of short-season varieties of common bean, cowpea and lablab. Sowing date influenced the phenological development of all legumes (Table 9). Early planting before the onset of the rain led to accelerated development opposed to late sowing after the beginning of the rains, reflecting the requirement of minimum soil moisture for successful germination and emergence. Significant impacts of sowing date on biomass and grain yield determination were only observed for cowpea. Early sowing was favourable against late sowing. This reflected a better use of limited in-season rainfall during the restricted growing period if planted early enough. Plant density had different effects on biomass and grain yield accumulation of the different legume species. Little difference was observed on cowpea biomass and grain yield planted at low, medium and high plant density indicating high compensation of low plant densities by the growth habit.

The impact of plant density on lablab growth was more noticeable, reaching higher LAI, biomass and yield at higher plant densities. Lablab biomass and grain yield were almost doubled for high (LAI: 1.8 – 2.0, biomass: 4.1 – 4.7, yield: 2.2 – 2.4 t ha^{-1}) in comparison to low plant densities (LAI: 0.6, biomass: 2.3, yield: 1.2 t ha^{-1}). The characteristic compact plant architecture of lablab make a compensation of plant density by growth habit rather difficult. Simulation results were similar for common bean, where plant density had a higher impact on biomass and yield accumulation than sowing date, highlighting similarities in plant morphology and growth habit of common bean and lablab.

Additionally management practices influencing water availability, i.e. represented in the soil water status, is one of the most important factors affecting yields in rainfed agriculture. However, the yield potential and the impact of in-season rainfall on the grain yield of the different short-season legume species showed large differences (Figure 8). There was a clear trend of increased yield with increased in-season rainfall for all legumes, but the magnitudes among the legumes differed to a large extend. The yield potential of short-season varieties of common bean in semi-arid areas of Eastern Kenya was restricted to 2 t ha^{-1} even in years with high rainfall. Potential yields were obtained from 250 mm and more in-crop rainfall. Cowpea yield was highly responsive to in-season rainfall and higher in-crop rainfall mainly boosted grain yield. In years with above-average rainfall of 800 mm, yields of almost 6 t ha^{-1} were achieved. In wet years, cowpea out-yielded common bean and lablab, but in years with rainfall of 200 mm or less, obtained grain yields were even below those of common bean. Grain yield of lablab increased linearly up to 400 mm rainfall per season but stagnated from 400 mm at a level of about 2 to 3 t ha^{-1} depending on the plant density.

Table 9: Simulated time to flowering and maturity in days after planting (DAP), biomass and leaf area index (LAI) at 50 % flowering and total above-ground dry matter (DM) and grain yield at maturity in kg ha^{-1} for common bean, cowpea and lablab. The simulation scenario using APISM based on two sowing dates, early and late and three different plant densities. Mean (n=33) and standard deviation (in brackets) are presented.

Species	Sowing date	Plant density	Flowering [DAP]		Biomass at 50% flowering [kg ha^{-1}]		LAI at 50% flowering [-]		Maturity [DAP]		Total DM [kg ha^{-1}]		Grain yield [kg ha^{-1}]	
Bean	early	low	42	(7.4)	346	(162)	0.5	(0.19)	75	(15.3)	1836	(706)	957	(367)
		medium			593	(266)	1.0	(0.35)			2128	(815)	1122	(434)
		high			899	(376)	1.5	(0.59)			2431	(920)	1282	(488)
	late	low	37	(2.0)	352	(167)	0.5	(0.20)	71	(13.0)	1981	(894)	1021	(475)
		medium			609	(291)	1.0	(0.39)			2266	(977)	1176	(543)
		high			933	(438)	1.5	(0.69)			2522	(1053)	1300	(582)
Cowpea	early	low	82	(16.4)	3837	(1945)	3.2	(1.73)	114	(22.1)	4629	(2762)	1893	(1438)
		medium			4094	(2012)	4.1	(2.31)			4859	(2919)	1918	(1511)
		high			4361	(2110)	4.3	(2.43)			5061	(3044)	1950	(1571)
	late	low	76	(14.7)	3310	(1633)	2.5	(1.37)	107	(20.3)	3934	(2669)	1585	(1396)
		medium			3474	(1701)	3.1	(1.87)			4061	(2795)	1594	(1460)
		high			3640	(1803)	3.3	(2.00)			4174	(2906)	1600	(1509)
Lablab	early	low	81	(16.2)	1514	(321)	0.6	(0.06)	124	(23.6)	2303	(639)	1219	(376)
		medium			2547	(644)	1.1	(0.19)			3545	(1233)	1847	(713)
		high			3766	(1231)	2.0	(0.54)			4747	(2008)	2417	(1117)
	late	low	76	(14.5)	1581	(321)	0.6	(0.06)	116	(21.8)	2283	(689)	1204	(387)
		medium			2579	(692)	1.1	(0.21)			3320	(1286)	1724	(707)
		high			3550	(1221)	1.8	(0.51)			4104	(1953)	2100	(1048)

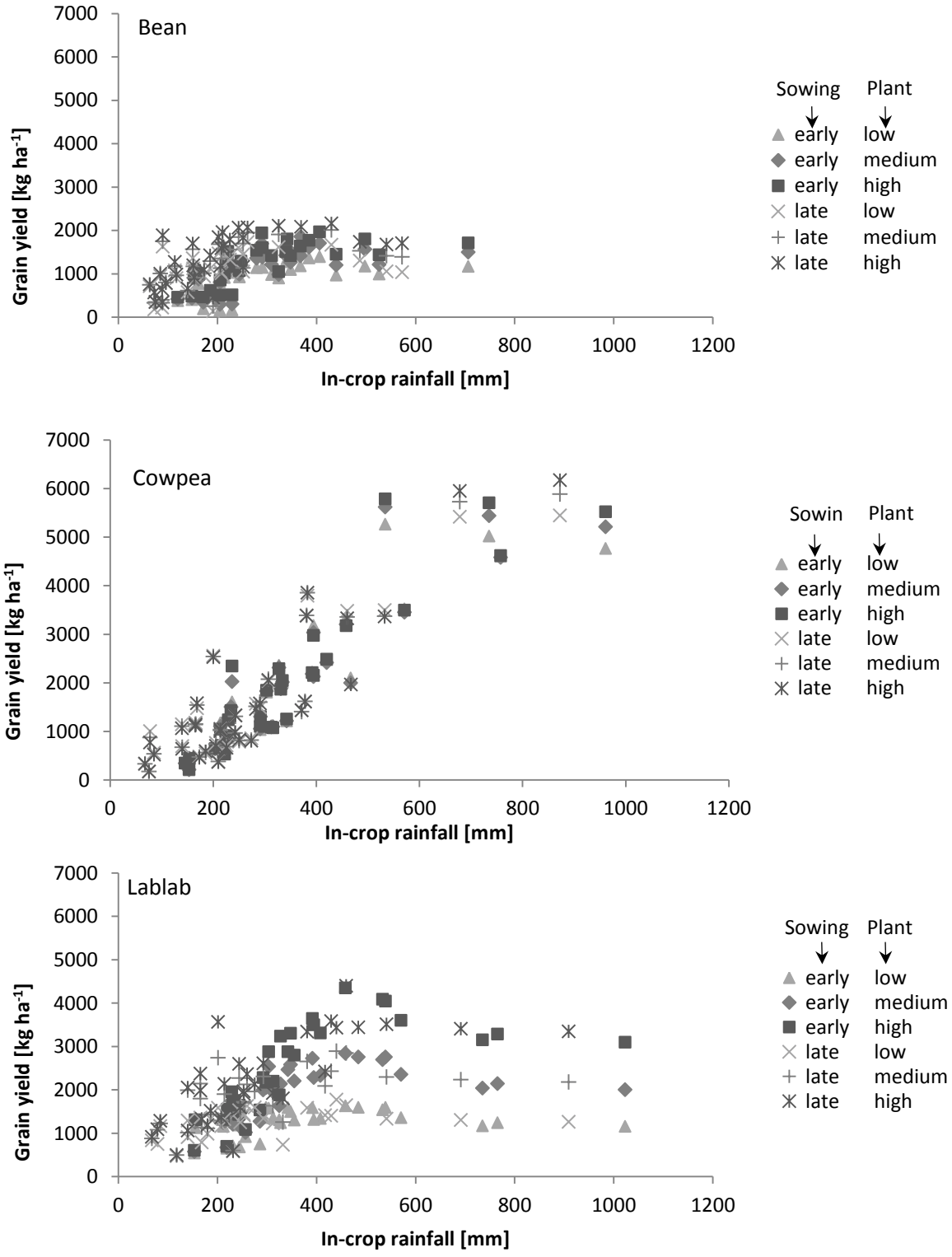

Figure 8: Simulated grain yield (kg ha^{-1}) of common bean, cowpea and lablab in relation to in-crop rainfall (mm) in Machakos, Eastern Kenya. The simulation scenario using APISM based on two sowing dates, early and late and three different plant densities run for 32 years from 1981-2014.

Discussion

Model performance

Phenology

The APSIM navy bean, cowpea and lablab model has not been previously tested for short-season varieties under semi-arid conditions. The cultivar-specific parameter changes made for common bean and cowpea and the cultivar-specific and species-specific parameter changes implemented for lablab according to in-field observations and measured data were appropriate to simulate their short-season and high-yielding character well. In particular the fit of observed and predicted phenological development was excellent. The models predicted flowering and maturity dates with an accuracy of less than five days (Table 6). The model framework used in the APSIM legume models, which employs the thermal time concept, can therefore account for the main cultivar and environment effects on phenology. Nevertheless, observed deviations in flowering and maturity time were founded in the distinctive phenological plasticity of legumes. It was observed that water deficit can accelerate flowering and that the duration of flowering was significantly reduced by water shortage (Muchow, 1985; Siddique et al., 2001; Thomson et al., 1997). Modification of phenology in response to water availability is also documented for lablab, where the growth duration was reduced by water deficit (Muchow, 1985). In contrast to cereal crops it is more difficult to determine the exact time of 50 % flowering and physiological maturity in the field due to the unsynchronized flowering of larger inflorescences and maturity of different pod sets. Furthermore, the observed overlap of defined growing periods (e.g. flowering and grain fill) is not considered by the APSIM model, where only one growing period determines the actual status of development. However, the time of flowering is an important determinant of adaption to the environment, in particular in semi-arid environments were yields can be limited by terminal droughts. Hence, the time of flowering needs to be optimized to allow maximum vegetative growth and, at the same time, enable seed development to be completed before the onset of severe drought stress. Therefore, the model accuracy of phenological events is very important for its application in challenging environments, including semi-arid Eastern Kenya.

Biomass growth and yield

The models were able to simulate common bean, cowpea and lablab biomass over an observed range of 1.8 – 3.7, 2.6 – 5.6 and 2.5 – 5.5 t ha^{-1}, respectively, and observed grain yields over a range of 1.0 – 2.0, 1.4 – 3.0 and 1.2 – 2.4 t ha^{-1}, respectively (Table 7). The model accuracy was different for common bean, cowpea and lablab, and the best fit was observed for common bean with RMSE of 370.2 kg ha^{-1} for predicted biomass growth and 191.9 kg ha^{-1} for grain yield. The degree of agreement between observed and predicted biomass and yield in the calibration and validation in this study was comparable or even better with that achieved for other single-species modules used in APSIM. RMSE values expressed in % of the observed mean of 53, 24, 22 and 29 were obtained for mungbean, peanuts, chickpea and pigeonpea, respectively (Robertson et al., 2002).

The prediction accuracy of this study determined RMSE values of about 12 % of the observed mean for common bean biomass and grain yield and between 20 and 26 % for cowpea and lablab biomass and grain yield. Therefore the predictive model capability achieved for the short-season grain legume varieties can be rated similar to or even better than that for other species simulated within the same framework.

Cultivar-specific parameters derived from field experiments, such as HI and daily increase in HI, were selected well to account for the high yielding characteristics of the studied short-season grain legumes. Similar high HI values were observed by Ayaz et al. (1999) for chickpea, lentils and peas. The HI is an important contributor to final yield but, at the same time, sensitive to crop management and environmental factors. Greatest physiological potential for genetic improvement in the productivity of tropical grain legumes is not accomplished through increased total biomass production, but was attained with improved HIs - one of the key achievements in past legume breeding and technology (Lawn, 1989). Stable HIs are still a major breeding goal for grain legumes (Akibode and Maredia, 2011). Short-season varieties, like the ones studied, were selected to reach a high HI in short time and are, therefore, promising candidates for farming with shortened cropping windows. Nevertheless, calculations of HI encounter many uncertainties. In particular the harvesting method or the moisture content can cause variations in calculated HI values (Unkovich et al., 2010). For crops, which drop leaves prior to maturity due to pronounced senescence like observed for the studied short-season legumes, HI should be calculated from peak biomass dry matter, including fallen leaves, not just from standing dry matter at maturity. In general, this is recommended for tropical legumes and has a considerable influence on the estimated HI value (chapter II). Furthermore, this would make calculated HI values better comparable for different plant species from different regions. However, APSIM uses HI values determined at harvest (proportion of grain yield to total above-ground biomass at physiological maturity) as benchmark parameters in the simulations. The cultivar-specific parameters HI and daily increase in HI used for the parameterization procedure should, therefore, be calculated similarly. Another important feature of legumes, in particular short-season varieties, is the remobilization capacity. Leaf nitrogen from senescenced leaves is translocated towards the pods and used to accumulate grain nitrogen (Sanetra et al., 1998). This is particularly important and advantageous when soil N uptake through biological nitrogen fixation decreases during drought events, especially towards the end of the cropping season; and it ensures high yield returns of these legume varieties. The pronounced leaf senescence observed for all short-season grain legumes in semi-arid areas is driven by the high remobilization efficiency. An extremely high efficiency of about 63 % N was reported for cowpea amounting 34 % of seed N (Peoples et al., 1983). Pigeonpea showed an even higher remobilization efficiency, meeting almost 50 % of the seed's requirement for N, if entirely transferred to the seed (Sanetra et al., 1998). The adaption of the translocation efficiency and the reduction of the proportion of structural biomass of leaf and stem plant parts within APSIM was a major and reasonable requirement to simulate the high yielding character of short-season lablab varieties. The present work confirmed the ability of the current model to simulate the response to different water regimes well. This is prerequisite to simulate growth and development of short-season legumes, in particular in semi-arid areas, were water availability is the most limiting factor for agricultural production (Black and Ong, 2000; Blum, 2005).

A wider range of biomass and grain yield for cowpea and lablab, achieved by the model testing with below or above recommended plant densities, revealed the need for more intensive model validation before more confidence can be placed in the models ability to simulate growth and development at high plant densities in semi-arid areas. Overall the relatively high RMSE values expressed in % of mean observed values for cowpea and lablab indicate the existence of unexpected sources of variation, e.g. spatial variation in soils, effect of weeds or feeding animals. In particular, spatial variation in soil characteristics is a common phenomenon observed on smallholder farms in Kenya (Tittonell et al., 2005). Therefore, model validation using more variable soil sites is recommended. However, most grain legumes are reasonably plastic in their response to changes in plant population (Ayaz et al., 2004), and it is challenging to account for the whole phenological flexibility of different legume species since growth habit and plant architecture change with plant density. There are a number of known characteristics of legume growth and development that are not accounted for in the present models, due to insufficient physiological understanding and comprehensive data to parameterize functional relationships. One is the extensive vegetative growth and the limited pod set development of lablab at higher plant densities. But similar was observed for peas where some plants produced pods with no seeds if planted at high densities (Moot and McNeil, 1995). Furthermore, APSIM is not yet able to simulate the occurrence of multiple flushes of flowers and pods after the experience of intermediate (drought) stress events. But this is in particular interesting, and might be an advantageous feature for farming with increased climate uncertainties, including prolonged drought spells within the rainy season in semi-arid areas, and it requires further investigation.

Sensitivity analysis

The sensitivity analysis highlighted, that the influence of essential physiological parameters had great impact on biomass growth and grain yield accumulation of legumes (Table 8). The effect of the influence revealed the most limiting factor for growth and development of each legume species. The very early maturing variety of common bean was less effected by water shortage throughout the growing period than cowpea. Cowpea had a prolonged vegetative growing period and accumulated high amounts of biomass and had a big canopy with more leaves than common bean (chapter II). Therefore, cowpea was more affected by drought than the compact and small common bean plant leading to a higher impact of changes in TE. Consequently, the potential growth of common bean was less limited by water in comparison with cowpea and lablab. Hence, potential biomass growth of the very early-maturing variety of common bean is primarily a function of the intercepted radiation and the radiation-use efficiency. Whereas the rather water-limited growth of cowpea is mainly a function of water supply and the transpiration efficiency, and actual biomass increase is simulated from either potential or water-limited growth as modified by temperature. Both RUE and TE affected lablab biomass and grain yield to a great extent. But the impact of changes in TE was less severe in comparison to cowpea. Consequently, lablab growth was less affected by drought. Hill et al. (2006) concluded that estimates based on values found in the literature for k and RUE as implemented in the APSIM lablab model are accurate.

Values for RUE of 0.9 and k of 0.7 obtained from field experiments and measurements in semi-arid Eastern Kenya reveal a great degree of agreement with the values implemented in APSIM (RUE: 1.0, k: 0.6) (chapter II). The same was true for common bean, where measured values matched the values used by APSIM. RUE, in combination with k, are key indicators to describe crop resource use; however, plant density and water availability can strongly influence these factors (Ayaz et al., 1999; Tesfaye et al., 2006; chapter II). This should be considered better by plant growth models, were RUE and TE are considered as function of development stage and not influenced by water limitation or other growth-limiting stresses and plant density. The impact of plant row spacing, for example, allows to mimic differences in k with plant density which is implemented in APSIM already.

Simulation experiment

Simulated yields are higher than those usually observed in farmers' fields due to the negligence of weed competition and nutrient constraints, which are usually observed in farmers' fields in the study area (Muhammad et al., 2010; Rao and Mathuva, 2000). Furthermore, the effects of pest and disease damage were not considered. Nevertheless, the linkage of the model with historical weather data, was used to assess probability distributions for yield and yield penalties associated with different management options. The simulated yield reflects water-limited yield for semi-arid Eastern Kenya under different management practices. Later sowing, after the onset of the rain, had relatively little impact on biomass accumulation and grain yield development of common bean and lablab, whereas both were reduced for cowpea (Figure 8). The amount of in-crop rain was most important for yield determination in cowpea, indicating a greater sensitivity to in-season drought spells of cowpea in comparison to common bean and lablab. Later sowing conceals the danger of missing the first important rain events for germination at the beginning of the rain season. In general, yield reduction due to water deficits was observed to be relatively high for cowpea than other tropical grain legumes (Muchow 1985). The date of sowing is therefore considered critically important particularly in order to achieve high grain yield returns of cowpea. However, dry sowing, before the onset of the rain, might be risky in practice, because of birds and other animals feeding on the seeds before germination, leading to high losses for the farmer. The early-maturing characteristics of common bean made the sowing date less important for the production success, allowing for more flexible cropping practices such as later sowing in inter-cropping systems with an associated cereal crop, for instance. Breeding towards shorter duration varieties of grain legumes has been the major objective, not only to match phenology to season length, but also for other reasons, such as to fit crops into more intensive crop rotations (Upadhyaya et al., 2011). The yield potential of lablab was lower in comparison to cowpea and the response to in-crop rainfall was less pronounced. However, lablab seemed to cope best with in-season rainfall variability and showed a comparatively high yield stability. Whereas the strategy of common bean is the exploitation of drought escape through the avoidance of external droughts by a shortened crop duration, lablab seemed to have integrated traits (chapter II), which allow to cope better with drought and make better use of the soil moisture over an extended growing period.

Lablab is regarded as a traditional African crop adapted to local environmental conditions and has evolved a range of morphological, phenological and physiological mechanisms to efficiently utilize resources, available in the production environment (Maass et al., 2010; Savitha, 2008). Relatively high yields of lablab even under dry conditions are in accordance with observations by Maundu et al. (1999) and the review by Maass et al. (2010). Consequently, lablab yielded relatively better than other grain legumes under dry conditions, thus, making genetic resources of locally adapted landraces and traditional species more important in the future, in particular in the view of global change (Subbarao et al., 1995; Vadez et al., 2012). Resource use and use efficiency are very complex mechanisms and different species seem to follow different strategies. The match of phenology to growing season is one of the most important approaches and the basis for efficient resource capture. Nevertheless, other plant physiological adaptions to control resource use are also important. In terms of water use, mechanisms to control water loss through dehydration avoidance or drought tolerance such as the regulation of stomata opening and adaption of root growth are further aspects considered essential (Vadez et al., 2012).

The effect of plant density on biomass and yield accumulation for cowpea was very low indicating an optimal resource use in terms of space and a great growth compensation ability. This is in accordance with findings of Muchow et al. (1993) and Craufurd and Wheeler (1999) confirming the conservative nature of biomass partitioning in cowpea. Consequently, grain yield is primarily determined by the ability to accumulate biomass even under dry conditions and different plant densities. Surprisingly, the plant density effect was fairly high for lablab. This highlights some limitations of the model. The current APSIM lablab model does not account for reduction in pod set development with increased plant density as observed in the field. Further work is required to better describe these density effects on lablab yield accumulation. However, the results of this study demonstrate the capability for simulating growth and development of short-season grain legume varieties under semi-arid conditions. APSIM has proven to be a model simple enough to derive required parameters for model calibration and at the same time exact enough to simulate growth and development at satisfactory comprehensiveness (Robertson et al., 2002). The calibration of commonly used short-season grain legume varieties in semi-arid areas will add to the model applicability by enabling simulation studies to develop climate smart agricultural strategies and help to better integrate grain legumes in smallholder farming systems. Hence, simulation models are great tools to capture the complexity by integrating multiple constraints. Further, the characterization of drought patterns and rainfall variability will require more flexible cropping strategies, and simulation modelling can predict water use in regard to climate change and, at the same time, the effect of management strategies on production success and farm sustainability (Subbarao et al., 1995). Additionally, simulation models can not only predict simple biomass and grain yield but can be used to assess the sustainability of a certain cropping strategy in regard to residue production and the impact on soil fertility.

Conclusion

The APSIM common bean (navy bean), cowpea and lablab model has been calibrated for short-season varieties with data from semi-arid Eastern Kenya .It was tested for the first time for flowering and maturity time as well as biomass and grain yield production for a range of plant densities and water regimes in two seasons. The prediction of the phenological development of the studied grain legumes was very good. Further, the model reproduced the effect of water availability on biomass accumulation and yield development well and the response to plant density with satisfactory accuracy for common bean and cowpea. A good relationship between simulated yield and in-crop rainfall underlined the importance of taking a water-limited potential yield into account when management practices are considered. The change of cultivar-specific parameters within APSIM was sufficient to parameterize APSIM for short-season varieties of common bean and cowpea. The critical parameters to adjust for proper parameterization needed, however, to be extended to species-specific parameters to calibrate for short-season lablab varieties as the prior calibration work focused on forage and perennial varieties only. Finally, the ability of simulating short-season grain legumes in semi-arid areas is the major achievement of this study as the use of these varieties has great potential for smallholder systems. Simulation models can be used to simulate benefits and risk of using such legume species for the farmer, farming systems and the environment. Furthermore, the application of simulation models can help to design site-specific climate smart agricultural cropping strategies considering the individual yield potential of the different grain legume species and changing environmental conditions.

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IV. Water use and use efficiency of short-season grain legumes in semi-arid Eastern Kenya – Coping with impacts of climate variability

Introduction

Eastern Africa is one of the most vulnerable regions to the impacts of climate variability and change (Boko et al. 2007, Challinor et al., 2007, Slingo et al., 2005, Thornton et al., 2011). Statistics on temperature and precipitation patterns reveal that most of Eastern Africa became warmer in the last century and that rainfall exhibits an increased inter- and intra-seasonal variability (Boko et al., 2007; Challinor et al., 2007; Cooper et al., 2009). Furthermore, erratic weather patterns characterized by cycles of droughts have become more frequent. Eastern Africa, including semi-arid areas of Eastern Kenya, is among the most vulnerable areas within Africa, as the resilience on climate-sensitive industries, particularly agriculture is the backbone of its economic development. Economic losses due to environmental vulnerability have been estimated to cost up to 40 % of the national gross domestic product (GDP) in Kenya (Thornton et al., 2006). Moreover, climate variability, in particular rainfall variability and associated droughts have been major causes of food insecurity. Challenges are particularly severe for small-scale subsistence farmers and in marginal rainfall areas. However, crop failure and reduced yields caused by water shortage within the growing period are common risks for rainfed cropping systems in semi-arid Eastern Kenya. Future climate scenarios show that increased rainfall variability, extended dry spells and increased soil evaporation due to higher temperatures will lead to even more decreased water availability in the future (Boko et al., 2007; Stern, 2007). Furthermore, Van de Steeg et al. (2009) indicate changes in growing season characteristics associated with climate change; growing seasons could become shorter changing the demand for crops and cropping system management in these areas.

Legumes display a wide agro-morphological diversity with great potential for adaption to challenging environments with the advantages of legumes in small-holder farming systems of Eastern Kenya widely acknowledged. The benefits of green manure, grain and fodder legumes for the farmer, farming systems, environment and economy have been reported in manifold publications (Graham and Vance, 2003). In particular, locally well-adapted short-season varieties of grain legume species from semi-arid areas such as common bean (*Phaseolus vulgaris* (L.)), cowpea (*Vigna unguiculata* (L.) Walp.) *and lablab (Lablab purpureus* (L.) Sweet) offer new possibilities for farming with increased uncertainties in risk prone environments, including new management options addressing the changes in growing season characteristics.

But a general problem is the lack of knowledge on the use of climate information and the adaption of agricultural interventions, such as short-season grain legume varieties to improve agricultural production. Simulation models have been proved to be an excellent tool to explore the potential of certain crops and cropping strategies in diverse smallholder farming systems and different environments (Whitbread et al. 2010).

African farming systems are highly heterogeneous, and simulation models manage to address the complexity of these systems, which is difficult through classical agronomic experiments alone (Robertson et al., 2001; Whitbread et al., 2010, Holzworth and Huth 2009). One of the most applicable models to better understand plant growth and development in response to the environment has been the Agricultural Production System sIMulator (APSIM) framework (Keating et al., 2003; Holzworth et al., 2014). Simulation models, such as APSIM can help to extrapolate field assessments of biomass and grain production as well as water-use and water-use efficiency of promising crops since they are able to capture the impacts of inter- and intra-seasonal rainfall variability as well as the variation in crop response to soil types and agronomic management. In particular, the interaction of phenology with patterns of water use and water use efficiency are key indicators of crop adaption to water-limited environments. But there is limited information available on the comparative water use and use efficiencies of short-season grain legumes in semi-arid environments.

Therefore, the study objectives were first to understand and characterize the variability and agro-climatic changes and associated risk for rainfed crop production systems along the Machakos-Makueni transect in semi-arid Eastern Kenya. The second objective was to examine water use and water-use efficiency of short-season grain legumes in semi-arid Eastern Kenya through classical agronomic field experiments. Further, the third objective was to simulate water use and use efficiency as well as the productivity of short-season grain legumes for different sites and soil types along the environmental gradient Machakos-Makueni in semi-arid Eastern Kenya using APSIM. Finally, the aim was to assess the overall performance of the promising short-season legumes at different sites (potential rainfall areas) and evaluate the impact of various soil types to estimate their agricultural production potential. This could help to better channel agricultural interventions to design more resilient and productive farming systems in semi-arid Eastern Kenya in the view of climate change.

Material and methods

Description of the study area

The study area is located in the predominantly semi-arid Eastern Province of Kenya and covers the Machakos – Makueni transect, which forms an environmental gradient of decreasing altitude, increasing temperatures, and decreasing moisture from the northwest to the southeast; resulting in a wide range of agro-ecological conditions (Figure 1 and Figure 2) (Jaetzold et al., 2006). The physical settings (topography and elevation) mainly influence the quantity and distribution of rainfall. The precipitation pattern is bimodal, with the locally known short rain season from October to February and a so-called long rain season between March and June. The amount of rainfall decreases along the transect from Machakos to Makueni: total annual averages are between 1,300 and 350 mm (Gichuki, 2000). Mean annual temperatures range from 17 °C to 24 °C. Farm size and population density across the research area are mainly driven by the availability of water and soils to sustain agriculture.

In medium potential areas of the upper midlands in the northwest, farm size is rather small ranging from 0.5 ha to 1.5 ha, whereas in the low potential areas of the lower midlands in the southern parts, farm size is comparatively large: 3 to 5.5 ha, compensating for the low productivity (Jaetzold et al., 2006)**.** Land use and livelihood are dominated by small-scale mixed farming systems: based on rainfed crop production combined with different levels of livestock rearing. Main crops grown on the mainly family owned farm land are maize and common bean (Muhammad, 2010).

Analysis of climate variability

The temporal variability expressed in various rainfall and temperature indices was evaluated at selected weather stations within the study area, based on the analysis of particular indicators representative for defining variations and extreme conditions (Stern et al., 1982). The rainfall indices included values of accumulated rainfall (monthly, seasonal, annual), number of rain days, mean daily rainfall intensity, start of growing season, end of growing season, length of growing season, and dry spell probability. The temperature indices were the annual minimum and maximum and mean annual temperatures, and number of days with temperatures exceeding 25 °C. Data management and statistical analysis was performed with R 3.1.1 (R, 2008).

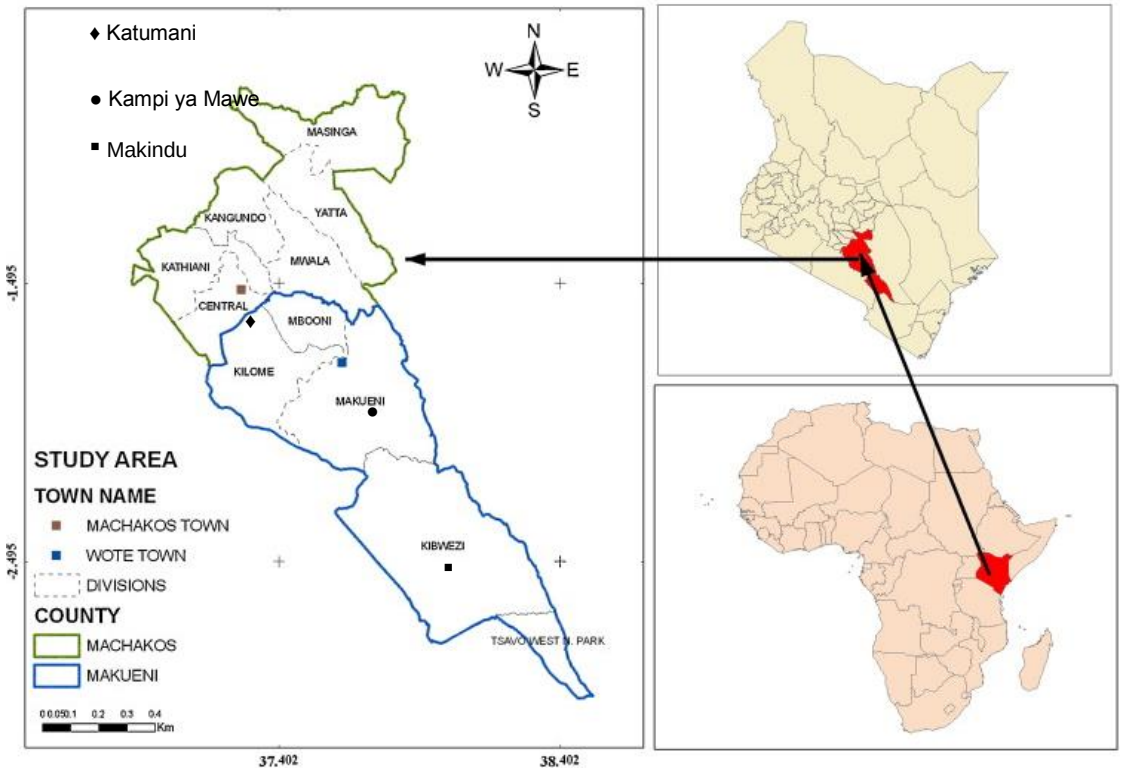

Figure 1: Location map of the study are: Machakos and Makueni County, Eastern Kenya including the study sites: Katumani, Kampi ya Mawe and Makindu (adapted from Wambugu 2011).

Data source

Daily weather data was obtained from the meteorological stations of the centers and sub-centers of the Kenyan Agricultural Research Institutes (KARI) in the study area including Katumani, Kampi ya Mawe and Makindu. Radiation data was partly obtained from the National Aeronautics and Space Administration (NASA) database for Climatology Resource for Agroclimatology (http://power.larc.nasa.gov/cgi-bin/cgiwrap/solar/agro.cgi?email=agroclim@larc.nasa.gov).

Two stations (Katumani and Kampi ya Mawe) were selected, which have relatively long periods (at least 30 years) of data records with no more than 5 % missing values for rainfall and temperature to obtain detailed climate variability analyses (Table 1).

Analysis of rainfall and temperature variability

Spatial distribution of the mean annual rainfall for the study area is illustrated in (Figure 2) (Jaeztold et al., 2006). The temporal rainfall variability for the three study sites in Eastern Kenya was first determined by calculating the coefficient of variation (CV) as the ratio of standard deviation to the mean annual rainfall in a given period. Further the mean monthly rainfall over the year was determined for all three sites along the transect. For temperature long-term daily data sets of Katumani and Kampi ya Mawe were examined on annual and seasonal basis.

Table 1: Geographical information as well as, availability of rainfall, temperature and radiation data for the study sites in Eastern Kenya.

Site	Latitude	Longitude	Elevation	Data		
				Rainfall	Temperature	Radiation
Katumani	1°34´56´´S	37°14´43´´E	1592 m	1961-2013	1981-2013	1981-2013
Kampi ya Mawe	1°51´0´´S	37°40´0´´E	1150 m	1961-2012	1970-2012	1981-2012
Makindu	2°16´58´´S	37°49´58´´E	1070 m	1997-2013	1977-2013	1997-2013

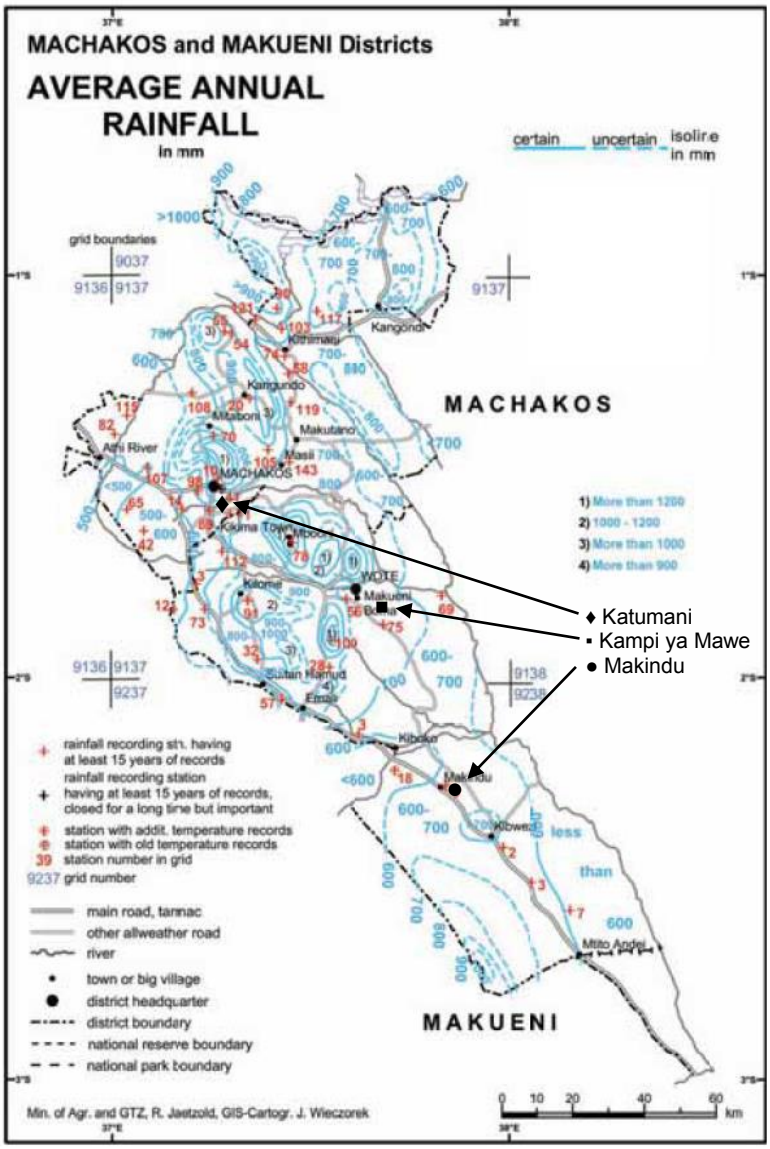

Figure 2: Location map of the study areas in Machakos and Makueni County, Eastern Kenya with spatial distribution of its mean annual rainfall (Jaeztold et al. 2006).

Analysis of growing season characteristics

The beginning of a rain season or growing period can be defined as the first occurrence of at least ´X` mm of rainfall over ´t` consecutive days (Stern et al., 1982). The potential start is a true event if the absence of any dry spell of ´n` or more days within the next confined period of ´m` days is assured. According to the environmental conditions and farmers` practice in the study area the earliest start of a rain season was defined as the first occasion with 20 mm rainfall or more within a 3-day period and no dry spell exceeding 10 days in the following 30 days.

Since the study area is characterized by a bimodal rainfall pattern the 1st of October was set as the earliest possible planting date for the short rain season and the 1st of March for the long rain season (Muhammad et al., 2010; Stern and Cooper, 2011). The end of the growing season is determined by stored soil water and its availability to the crop after the rain stopped. According to Stern et al. (1982), the end of a season is defined as the first date on which soil water is depleted. In the present study, the end of the short rain season was demarcated as any day after the 1st of January and for the long rain season after the 1st of May when the soil water balance reaches zero and no more than 5 mm of rainfall were recorded within 20 days. The length of each growing period was determined and analyzed for each site and year.

The dry spell probability at each site was estimated on the basis of generalized linear models for binomial responses using the complementary log-log link function (selected according Akaike information criterion (Akaike, 1973)) of dry spells > 5, 7, 10 or 15 days. The smooth effect function for Julian day of year were specified according cyclic P-splines (Eilers and Marx, 1996). All calculations were performed using R 3.1.1 and, in particular, package mgcv (Wood, 2011).

Water use: evidence from on-station trials

An experimental trial was designed to quantify the response of the short-season legumes to water availability over two seasons in semi-arid Eastern Kenya. The objective was to evaluate the water-use efficiency in on-station experiments to better estimate their agricultural potential for semi-arid areas.

Study site, experimental design and trial details

The experimental trial was conducted at KARI, Katumani in Machakos, Kenya to compare the growth, development and water use of three different short-season grain legumes (common bean, cowpea and lablab) in semi-arid areas. Locally adapted and commonly used short-season varieties recommended by KARI for cultivation in small-scale farming systems in semi-arid areas were used in the experiments; KAT X56 for common bean, M66 for cowpea and DL1002 for lablab. Phenological and growth characteristics of the different legumes are summarized in Table 2. The water response trial is described in detail in chapter II and was conducted during the growing period of the short rain in 2012/13 and 2013/14 (November - March). In short, the water response trial included three different water treatments; purely rainfed, partly irrigated (total 50 mm per week with additional drip irrigation till bud formation, i.e., onset of flowering), fully irrigated (total of 50 mm per week with additional drip irrigation throughout the growth period). All plots were established using the optimal plant density for cropping in semi-arid areas as recommend by KARI with a row-spacing of 50 cm for common bean and cowpea and 80 cm for lablab. Final plant densities were 10 plants m^{-2} for common bean and cowpea and 4.17 plants m^{-2} for lablab. Sowing was realized with the onset of the rain at 14th of November in 2012 and at 5th of November in 2013.

Table 2: Description of phenological development and growth characteristics of short-season grain legumes in semi-arid Eastern Kenya.

Species	Variety	Time to 50% flowering [DAP]	Time to physiological maturity [DAP]	Growth habit	Canopy architecture
Bean	KAT X56	37-41	69-78	Bushy	Compact, small
Cowpea	M66	61-66	84-92	Spreading	Widespread, large
Lablab	DL1002	57-60	98-104	Bushy	Compact, large

Measurements

Weather

At the study site, daily minimum and maximum temperatures as well as rainfall were recorded on daily basis. Further, solar radiation records were obtained from the meteorological station at KARI Katumani. If applied, irrigation records were documented.

Soil

The trials were located on fairly well-drained reddish brown chromic Luvisols with a clay texture throughout the profile, but an increased sand content at the surface layer (Jaetzold et al., 2006). The soil was slightly acid to neutral with a pH ranging from 5.5 to 7, and fairly poor in plant nutrients such as nitrogen, phosphorus, calcium, and zinc and with a relatively low organic matter content (OC ≤ 1 %). At sowing, 50 % flowering, physiological maturity and throughout the experiments at 2-week intervals, the soil moisture at each subplot was monitored. Soil moisture was determined gravimetrically depth-wise for the top four layers (at 0-15, 15-30, 30-60, 60-90 cm). The volumetric soil water content was calculated by multiplying gravimetric water content at a given depth interval with the bulk density (BD) at the corresponding depth. Plant available water (PAW) was estimated from the soil moisture data and the species-specific crop lower limit (chapter III).

Dry matter production and grain yield

For each legume, treatment and season above-ground biomass and grain yield production in dry matter (DM) was determined at 50 % flowering and physiological maturity.

Water use calculations

On the basis of the measured data, evapotranspiration (E_t) was determined based on the hydrological approach using the soil water method (Rana and Katerji, 2000). This is an indirect method based on the principle of conservation of mass in one dimension applied to the soil, according to the equation:

$$E_t = \Delta W + P + I - D - R \qquad (1)$$

Where ΔW is the change in water stored over the period considered, P is the precipitation and I is the amount of irrigation applied. The change in soil water was calculated from the soil moisture measurements over the growing period. Rainfall and irrigation were taken from the meteorological records and experimental protocols. Drainage (D) and Runoff (R) were estimated with the help of a simulation model.

APSIM was calibrated with site-specific soil and crop-specific parameters as described in chapter III, and runoff and drainage were simulated for each season, legume species and treatment separately with site-specific weather files. However, soil conditions after rain and sequential water profile suggested that drainage was negligible and, therefore, not considered in this calculation. Runoff was only observed after heavy rains in 2013/14. E_t was determined separately for each legume species according to their phenological development and specific in-crop rainfall and irrigation events. Maximum depths of water extraction were mostly covered up to a depth of 90 cm. Therefore, ΔW determinations were restricted to 150 cm soil profile depth. Between sowing and the first day of measurements, E_t was assumed to be similar to bare soil evaporation (E_S) and estimated applying the Ritchie (1972) bare soil evaporation model. During that time, the soil was free of weeds and other vegetation cover. Soil parameters used for the model were derived from intensive on-site soil characterizations and data derived from prior soil characterization for sites at the KARI Katumani, research station in Machakos, Kenya by Gicheru and Ita (1987). The two parameters that determine first (U) and second stage (c) of soil evaporation were set to 4 and 2 mm day^{-1} ,respectively, representative for a sandy loam soil.

From the calculated and estimated E_t water use efficiency was determined. Therefore, the above-ground biomass and grain yield dry matter at harvest were divided by E_t to provide values on respective water use efficiencies, WUE_{DM} and WUE_{yield}:

$$WUE_{biomass} = \frac{Biomass}{E_t} \quad (2)$$

$$WUE_{grain} = \frac{Grain\ yield}{E_t}\ . \quad (3)$$

Simulation of water use

In order to extrapolate results of water use across time and space, simulation modeling in conjunction with long-term historical weather records was used to quantify the water use efficiency and the agricultural potential of the short-season grain legumes along the Machakos -Makueni transect.

APSIM

APSIM was used to simulate the growth and development of short-season legumes in semi-arid Eastern Kenya. Therefore the legume crop modules of common bean (navy bean), cowpea and lablab were parameterized for short-season varieties. Further the SOILWAT and SOILN modules were parameterized as described in detail in chapter III.

To estimate water us, essential parameters to be simulated are evapotranspiration and evaporation. The potential evapotranspiration in the APSIM model is calculated using an equilibrium evaporation concept as modified by Priestly and Taylor (1972) and implemented in the CERES models (Ritchie et al., 1985). Accordingly, soil evaporation is estimated as implemented in the CERES model (Ritchie et al., 1985) and assumed to take place in two consecutive stages. First stage (U) follows a wetting event and is energy-limited; in case the soil is sufficiently wet water is transported to the soil surface at a rate equal to the potential evaporation rate. Once the water content of the soil has decreased below a threshold value represented by U, the stage II (Cona) evaporation - limited by the hydraulic conductivity of the soil and determined by the diffucity settings of constant and slope – is providing water to the surface. Further, runoff is calculated from rainfall specified by the USDA-Soil Conservation Service procedure (curve number technique) based on soil texture (CN2Bare). The effect of surface residues is specified by the threshold surface cover (CNCov), above which there is no effect, and the corresponding curve number reduction (CNRed). Drainage occurs when all soil layers are saturated in the cascading water balance model and lost through the profile. Following, effective rainfall is defined as total precipitation minus runoff and drainage. Further in the APSIM model, water uptake is linked to the biomass production via transpiration efficiency and vapour pressure deficit (Monteith, 1988). Finally, simulated water uptake is a function of crop demand, the distribution of root length density, and available soil water in the different soil layers.

Simulation experiment

Three major soils from Eastern Kenya available in the International toolbox within APSIM were chosen to examine the effect of available water-holding capacity of the soil in interaction with site-specific rainfall characteristics and crop management on biomass production and grain yield development of short-season grain legumes. The first soil is a Chromic Luvisol with a high plant available water capacity (PAWC = 164 mm, Chromic Luvisol, Katumani Research Station), the second a clay loam soil (PAWC = 137 mm, Masii district, Kenya, clay loam, Alfisol) and the third a sandy soil with a low water-holding capacity (PAWC = 87 mm, Masii district, Kenya, sand, Alfisol) (Table 3). The difference between the soil-specific drained upper limit (DUL) and the soil- and plant species-specific crop lower limit (CLL) within the root zone was defined as extractable water-holding capacity of the soil. Root hospitality factors (X), which affect the ability of the crop to extract water form a certain soil layer, were fitted according to soil profile properties and legume species characteristics.

Long-term daily weather data including radiation data from the same sites, namely Katumani (1981-2013), Kampi ya Mawe (1981-2012) and Makindu (1997-2013), within the study area of Eastern Kenya as described in the climate variability analysis, were used for the simulations (Table 1 and Table 4). The simulation runs were started from the first of October after the long drought period. Soil water was reset to the lower limit (LL) on 1st of October. Between the short rain season (October-February) and the long rain season (March-June), soil water was not reset since the long rainy season partly depends on residual soil moisture of the previous short rains.

The initial nitrogen content was similar for all soils and reset at the beginning of each cropping period (1st of October and 1st of March) to eliminate a bias for nutrient availability on crop growth and development (NO_3 in kg ha^{-1}: 0-15 cm: 13.44, 15-30 cm: 9.525, 30-60 cm: 10.050, 60-180 cm: 3.93; NH_3 in kg ha^{-1}: 0-15 cm: 1.920, 15-30 cm: 0.191, 30-60 cm: 0.402, 60-180 cm: 0.399).

Table 3: Detailed description of soils used for the simulation study and their characteristics, including soil texture, plant available water capacity (PAWC) in mm, pH and organic carbon content in %.

Soil ID	APSIM soil name	Soil texture	USDA soil classification	PAWC[a] (mm)	pH[b]	Organic carbon[b] (%)
High PAWC	Chromic Luvisol, Katumani; Kenya	Sandy clay	Luvisol	164	6.0	0.92
Medium PAWC	Clay loam, Alfisol, Masii district, Kenya	Clay loam	Alfisol	137	6.0	1.10
Low PAWC	Sand, ALfisol, Masii district, Kenya	Sand	Alfisol	87	6.0	0.60

[a] Plant available water capacity
[b] measured for the 0-150 mm soil depth

Sowing time was controlled by a sowing rule and was aligned with growing season start. Sowing was realized after the 1st of October during the short rain season and after the 1st of March for the long rain season and did not occur unless at least 20 mm of rainfall were accumulated in 3 consecutive days with rain. Growth and development of short-season varieties of common bean, cowpea and lablab (Table 2) were simulated for both the growing period of the short rain season and the long rain season. Plant density was set according to the recommendations of KARI for cropping in semi-arid areas and similar to the water-response trial. For common bean and cowpea a row spacing of 50 cm with a final plant density of 10 plants m^{-2} was selected. For lablab the row spacing was set to 80 cm and the final plant density to 4.17 plants m^{-2}. Sowing depth was at 30 mm. All planting rules represent current ´best farmers` practice`. Phenological development (time to 50 % flowering and physiological maturity), biomass and grain yield production were simulated. Further water use was analyzed in relation to the phenological development, and water-use efficiency was estimated according to site- and soil-specific evapotranspiration relative to crop productivity. $WUE_{biomass}$ and WUE_{grain} were defined as the ratio of total biomass and grain yield, respectively, to evapotranspiration (E_t) between sowing and harvest.

Statistical analyses

To analyze the data from the experimental trial, biomass and grain yield as well as water use indices were compared among legume species and treatments, using analysis of variance (ANOVA). Each field trial and season was analyzed separately because of environmental variations. Within the species, the treatments effects were characterized using test of significance post-hoc multiple comparison Tukey test. To assess intra-specific differences in water-use efficiency data corresponding to the rainfed treatment only were extracted and the least significant differences (LSD) were computed. The significant differences among treatments were compared with the critical difference at 5 % level of probability. All statistical analyses were computed using R 3.1.1 (R 2008).

Results

Climate variability

General growing season characteristics

Within the Machakos – Makueni transect in Eastern Kenya the spatial distribution of rainfall is linked to physical settings, mainly topography and elevation. High potential rainfall areas are located in the hilly areas of the north-western parts, whereas rainfall decreases with altitude towards the southeast (Figure 2). Similar is represented in the mean annual rainfall of the three study sites along the transect within the research area, with the highest mean annual rainfall records for Katumani (996 mm), medium for Kampi ya Mawe (640 mm) and the lowest for Makindu (545 mm) (Table 4). The rainfall pattern is clearly bimodal across the study area (Figure 4). The first growing period starting at the end of October (until February), the so-called short rain, received on average more rain than the growing period of the long rain (March – June). During the short rain, Katumani and Kampi ya Mawe received on average almost 400 mm per season, whereas the mean seasonal rainfall during the long rain was less than 300 mm for all sites. In Makindu, the mean seasonal rainfall of the short rain is 100 mm lower compared to the high and medium potential rainfall sites Katumani and Kampi ya Mawe respectively. Katumani and Makindu showed moderate variation in annual rainfall (CV: 28-30 %). The seasonal variation in rainfall was however high for all sites. For Kampi ya Mawe the calculated coefficients of variation were much higher for the growing period of the long rain in comparison to the short rain, indicating a comparatively high intra-seasonal rainfall variability for the growing period of the long rain.

Table 4: Rainfall and the respective coefficient of variation (CV) for three study sites in Eastern Kenya, including Katumani, Kampi ya Mawe (KyM) and Makindu calculated from different datasets as indicated in Table 1..

Site	Temperature (°C)			Rainfall (mm)					
				Annual		Short rain		Long rain	
	Mean	Maximum	Minimum	Mean	CV (%)	Mean	CV (%)	Mean	CV (%)
Katumani	21.0	26.2	15.8	695.8	28.0	391.5	42.4	290.6	41.1
KyM	23.0	28.9	17.1	639.6	35.9	383.7	41.0	247.7	51.9
Makindu	22.2	27.7	16.7	544.5	30.1	281.3	39.9	227.4	34.6

Temperature variability and trends

The mean annual temperatures within the study area ranged from 21 to 23 °C and was highest in Kampi ya Mawe but lowest at the higher located Katumani with mean annual minimum and maximum temperatures ranging from 15.8 to 17.1 and 26.2 to 28.9 °C, respectively (Table 4). For both sites Katumani and Kampi ya Mawe, mean annual minimum and maximum temperatures showed a warming trend over the years. In Katumani, an average increase of the mean annual minimum temperature of 0.5 and the maximum temperature of 0.8 °C per decade was observed (Figure 3). This was similar to in Kampi ya Mawe, where the increase was slightly higher for the minimum temperature (0.9 °C per decade), but lower for maximum temperature (0.6 °C per decade). The comparatively pronounced trend of increasing mean maximum temperatures in Katumani is partly driven by a large increase in days with maximum temperatures above 25 °C, which was observed for both growing periods (the short rain and the long rain) during the last three decades (Figure 3). The number of days with maximum temperatures above 25 °C did not increase dramatically from 1970 onwards in Kampi ya Mawe but was, however, always on a higher level compared to Katumani due to lower elevation (Table 1).

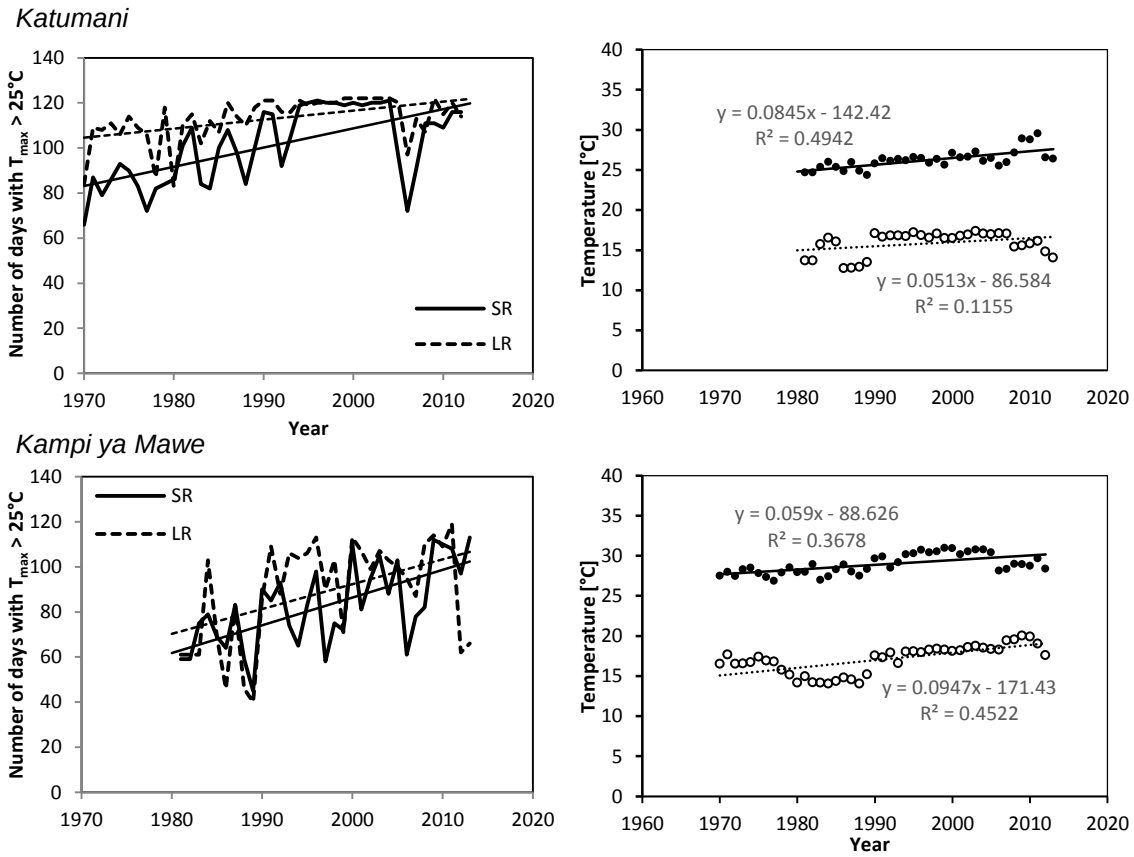

Figure 3: Time series and trends for minimum (○) and maximum (●) temperatures as well as number of days with maximum temperatures > 25 °C for the growing period of the short rain (SR,—) and long rain (LR,---) at Katumani and Kampi ya Mawe, Eastern Kenya.

Rainfall variability and trends

The rainfall pattern at all sites within the study area was bimodal. Two peaks within the monthly rainfall distribution over the year were discernible, one during the growing period of the short rain – in October and another during the long rain – in April. The month with the highest rainfall was November in Katumani and Kampi ya Mawe, and April in Makindu (Figure 4). From June till September, mean monthly rainfall was lower than 20 mm. This period is known as the dry season. In general, the standard deviation was very high indicating a high variation in accumulated monthly rainfall from one year to another.

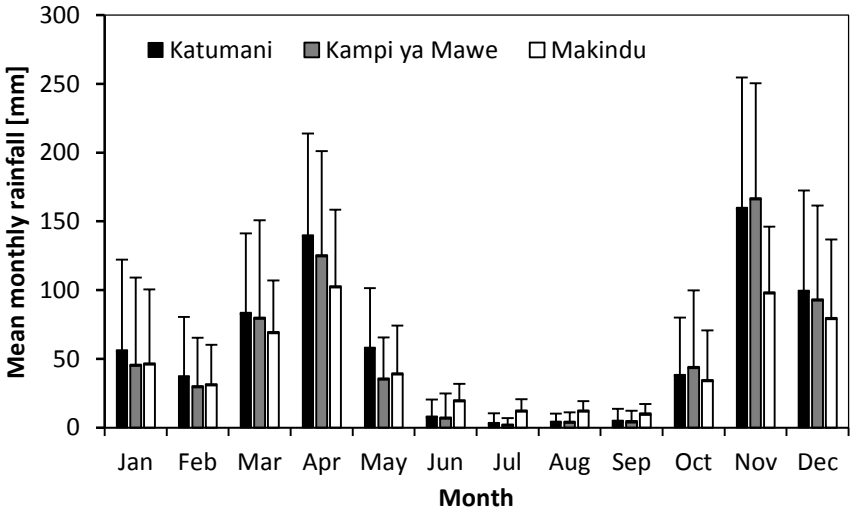

Figure 4: Monthly rainfall distribution with standard deviation for Katumani (period: 1961-2013), Kampi Ya Mawe (period: 1961-2012) and Makindu (period: 1997-2014) Eastern Kenya.

Analyses for the seasonal rainfall of the two selected stations, Katumani and Kampi ya Mawe, indicated that rainfall during the growing seasons in Eastern Kenya generally exhibited a high inter-seasonal variability. In the growing period of the short rain, total rainfall varied from 137 to 889 mm (CV: 41.2 %) in Katumani and from 151 to 778 mm in Kampi ya Mawe (CV: 41.0 %) within the last four decades (Figure 5). The recorded maxima of seasonal rainfall during the long rain were lower but inter-seasonal variability was higher, in particular for Kampi ya Mawe. The total rainfall accumulated during the long rain ranged from 55 to 539 mm (CV: 42.2 %) in Katumani and 43 to 631 mm (CV: 51.9 %) in Kampi ya Mawe. Whereas the trend in mean seasonal rainfall accumulation was stable over the last for decades in Katumani, a decline in total seasonal rainfall was observed for Kampi ya Mawe, in particular for the growing period of the long rain.

When analyzing the number of rainy days and the daily rainfall intensity (mean rainfall per rainy day), results indicated that during the growing period of the short rain the rainfall intensity is slightly higher at both sites, Katumani (SR: 8.3 LR: 7.9 mm per rainy day) and Kampi ya Mawe (SR: 8.8, LR: 8.1 mm per rainy day) (Figure 6). The trend showed a very slight decline for the short rain over the last four decades at both sites, whereas records for the long rain show only a decreasing trend for Kampi ya Mawe and slightly increasing for Katumani, however, they were not statistically significant.

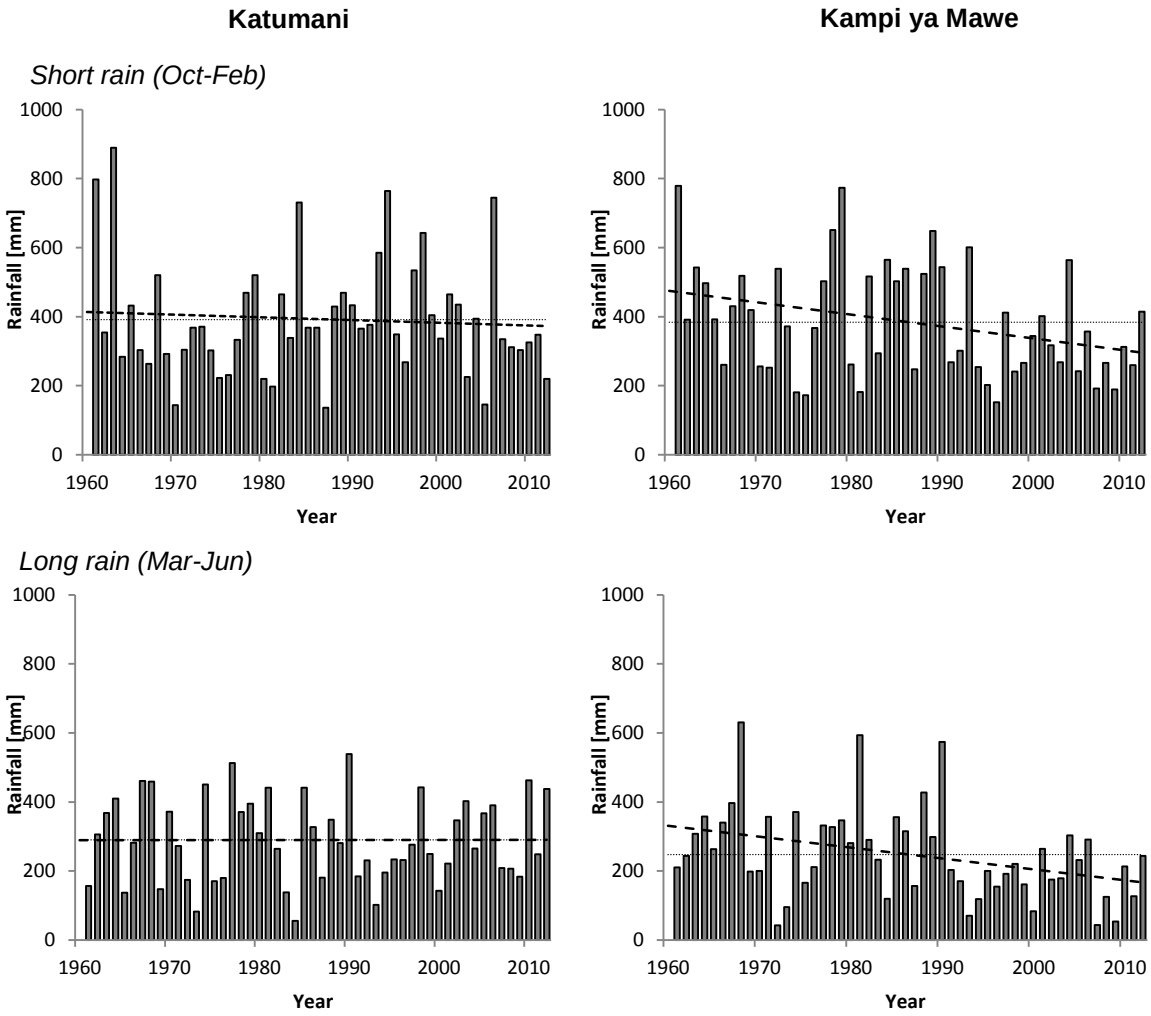

Figure 5: Mean seasonal rainfall for short rain (October - February, top) and long rain (March – June, bottom) periods for Katumani (period: 1961-2012, left) and Kampi ya Mawe (period: 1961-2012, right), Eastern Kenya; including the overall mean seasonal rainfall (dotted line) and the trend (dashed line).

During the growing period of the short rain, the number of rainfall days varied from 16 to 66 days in Katumani and from 17 to 69 in Kampi ya Mawe and from 13 to 48 and 8 to 64 for the long rain, respectively. The mean number of days with rainfall within each growing period was lower for the long rain in comparison to the short rain, and less rain days were recorded for Kampi ya Mawe (SR: 37 LR: 25 rainy days per season) if compared to Katumani (SR: 43, LR: 32 rainy days per season).

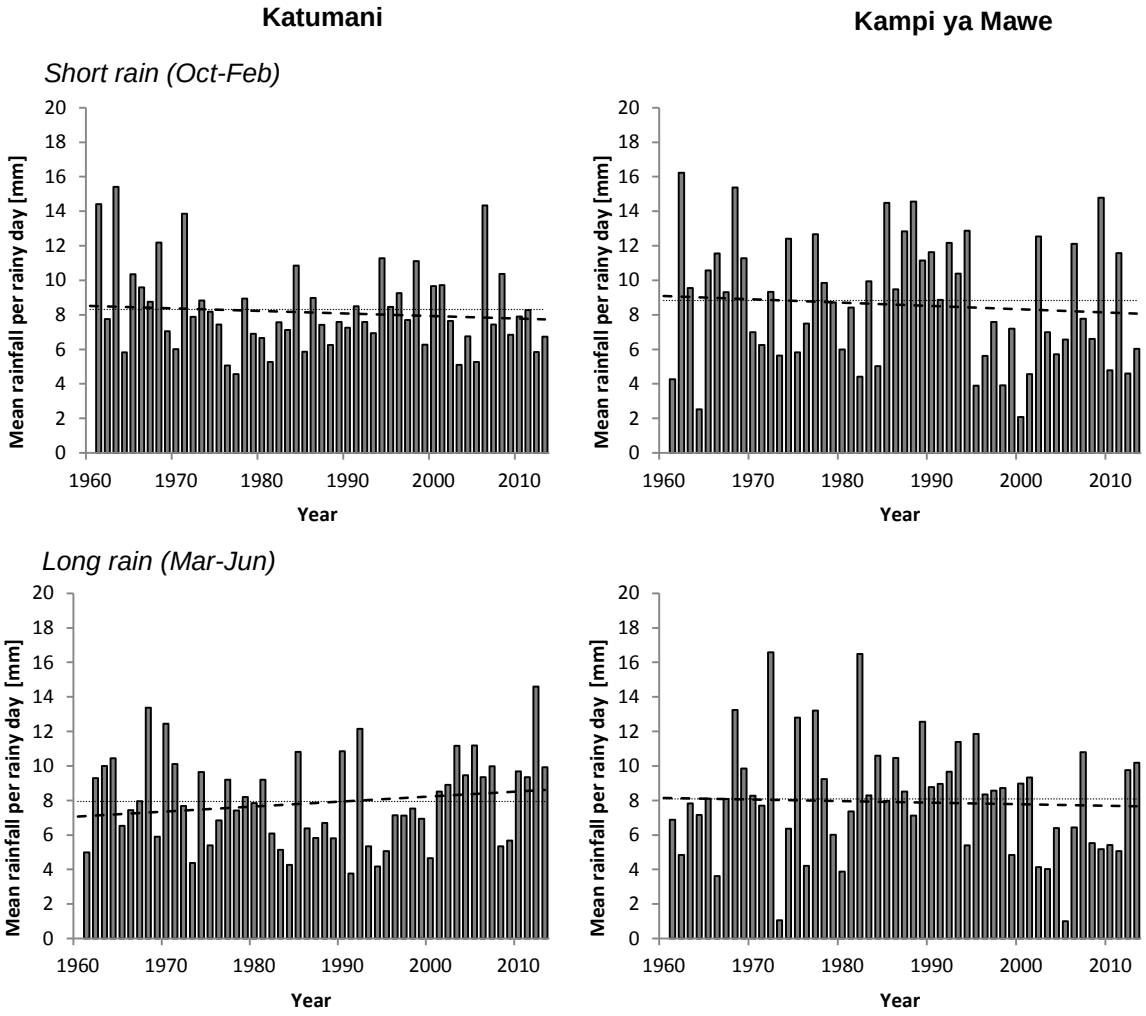

Figure 6: Rainfall intensity as mean rainfall per rainfall day during the short rains (October - February, top) and long rains (March – June, bottom) for Katumani (period: 1961-2012, left) and Kampi ya Mawe (period: 1961-2012, right), Eastern Kenya; including the mean rainfall intensity (dotted line) and the trend (dashed line).

In summary, Kampi ya Mawe was hotter and drier in comparison to Katumani with lower mean annual and seasonal rainfall and higher inter-seasonal rainfall variability and more extreme temperature events. Results further indicated that not only the total seasonal rainfall decreased over the last decades, in particular in Kampi ya Mawe, but also the rainfall intensity per rainy day.

Growing season length and dry spell analysis

The analysis of the season start and length revealed a high inter-annual variability similar to the high variability observed for the interseasonal and annual rainfall at both sites Katumani and Kampi ya Mawe (Figure 7). The short rain started a bit earlier in Katumani (Julian day number 308 (4th November)) in comparison to Kampi ya Mawe (Julian day number 310 (6th November)) and was longer (Katumani: 76 (53-92) days, Kampi ya Mawe: 66 (49-81) days). The 25 and 75 % percent quartile - a measure of the long-term variability – was particularly wide for the season start (short rain) in Katumani ranging from Julian day number 298 to 316. In general, it was true that the season length decreased the later the season started. Similar trends were observed for the long rain season, which started slightly earlier and was longer in Katumani in comparison to Kampi ya Mawe. The observed variability in season start (inter quartile range: Julian day number 73 – 101) and length (inter quartile range: 51 – 86 days) was, however, much higher for Kampi ya Mawe compared to Katumani for the long rain season.

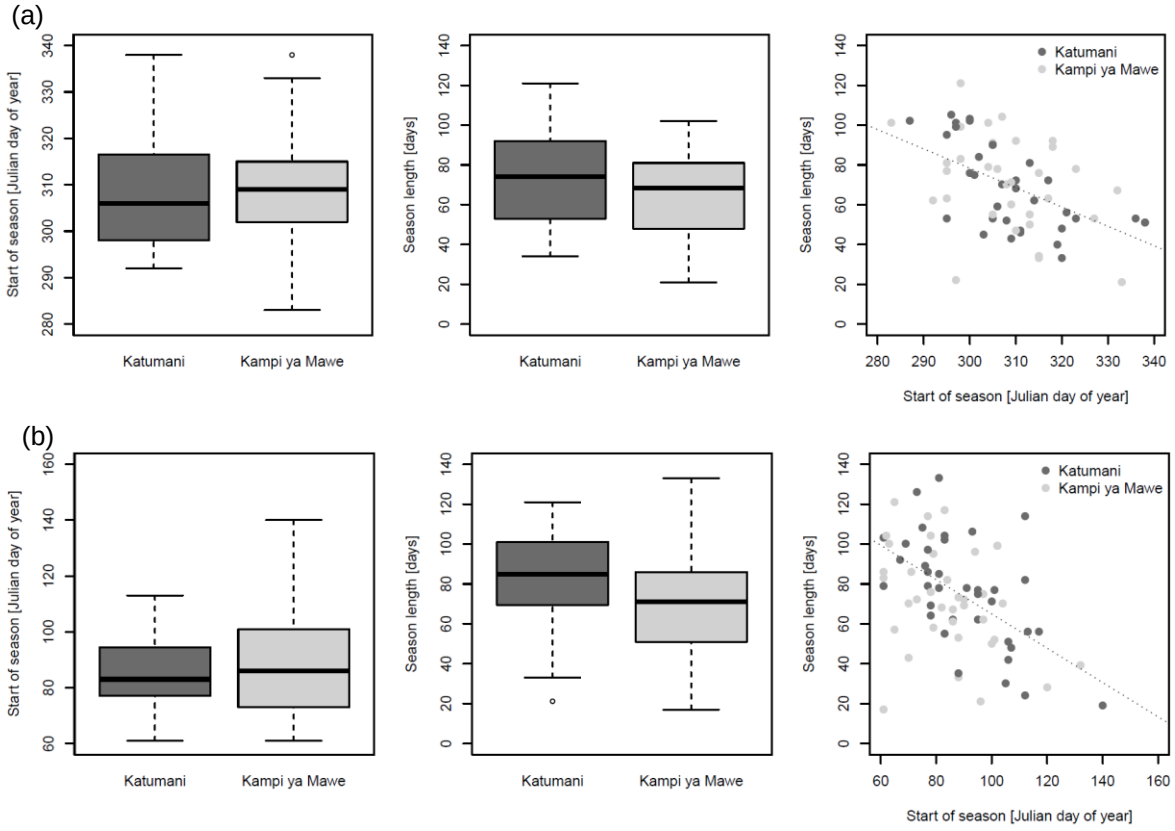

Figure 7: Boxplots representing characteristics of growing season length in Katumani and Kampi ya Mawe, Eastern Kenya, including start of growing season (day of the year, DOY) and growing season length (days) as well as the relationship between start of growing season and growing season length for the short rain (a) and the long rain (b) according to data as described in Table 1.

The high degree of variability in the start of each growing season and growing season length demonstrates the high degree of uncertainty aligned with cropping activity planning and adds to the risks for faming practice in Katumani and Kampi ya Mawe. The risk of crop failure due to early planting is as high as the chance of complete crop failure caused by an early season ending, as the season length is highly correlated to the season start for both the short and long rain season.

The dry spell analysis clearly shows the bimodal distribution of rain and dry seasons throughout the year (Figure 8). The probability of occurrence of longer dry spells was particularly distinct from July until September and at the end of February (the short and long rain season). The dry spell probability is, however, higher in Kampi ya Mawe at the end of February in comparison to Katuamani, indicating a pronounced dry period between the seasons. Even within the rain season, the probability of dry spells longer than five and seven days is higher in Kampi ya Mawe (18 and 12 % respectively) than in Katumani (15 and 9 % respectively), particularly for the long rain, characteristic for the rather unreliable long rain season. In general, the long rain had higher probability of in-season dry spells than the short rain.

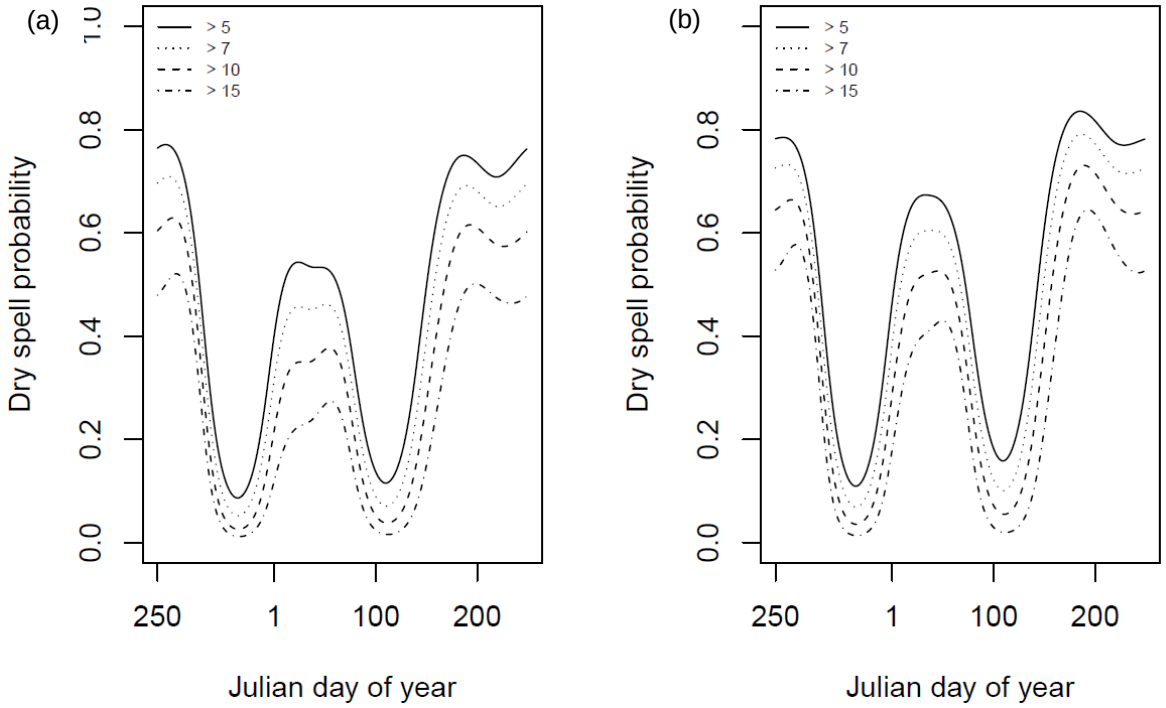

Figure 8: Probability of dry spells longer than 5, 7, 10 or 15 days length throughout the year (including the growing period of the short rain and the long rain) for (a) Katumani and (b) Kampi ya Mawe, Eastern Kenya.

Water use: evidence from on-station trials

Weather

Temperature patterns were fairly similar during the growing period of the short rain in 2012/13 and 2013/14, with mean minimum temperatures of 15 °C and mean maximum temperatures of 31 °C. The absolute minimum temperatures measured within each season were 10 and 11 °C, while the absolute maxima were 42 and 40 °C in 2012/13 and 2013/14, respectively (Figure 9). In both years, the average temperature was 23 °C and slightly above long-term average. In contrast to the similar temperature patterns, rainfall intensity and distribution were different during the short rains of 2012/13 and 2013/14. In the growing period rain was below the long-term average (Claessens et al., 2012; Rao and Okwach, 2005) in 2012/13 with 262 mm only, but relatively evenly distributed between November and January but no rain in February. During the short rain of 2013/14, total rainfall was about long-term average, and almost 100 mm more rain was recorded than in the previous year (354 mm). But in 2013/14, rain was distributed very unevenly, with 220 mm falling between end-November to end-December as heavy rains and a long in-growing period dry spell occurring from 22nd December to 6th February.

Water use efficiency

Detailed data representing the phenological development as well as biomass and grain yield accumulation of the short-season legumes in semi-arid Eastern Kenya were presented in chapter II. In brief, common bean proved to be a true short-season crop, and first flowering was observed already five to six weeks after planting with grains ready to harvest after two to two and a half months. Lablab flowered earlier (43-47 DAP) than cowpea (47-54 DAP), however, time to physiological maturity was longest for lablab with 98–104 DAP. The temporal pattern of phenological development are partly reflected in their growing season water use and water-use efficiency. The water use was always lowest for common bean independent of the water treatment applied caused by the fast phenological development (Table 5). The water use of lablab was always highest due to the long maturity time. Biomass production and grain yields were not similar in the two distinct seasons, mainly caused by different total seasonal rainfall and temporal rainfall distribution over the growing seasons.

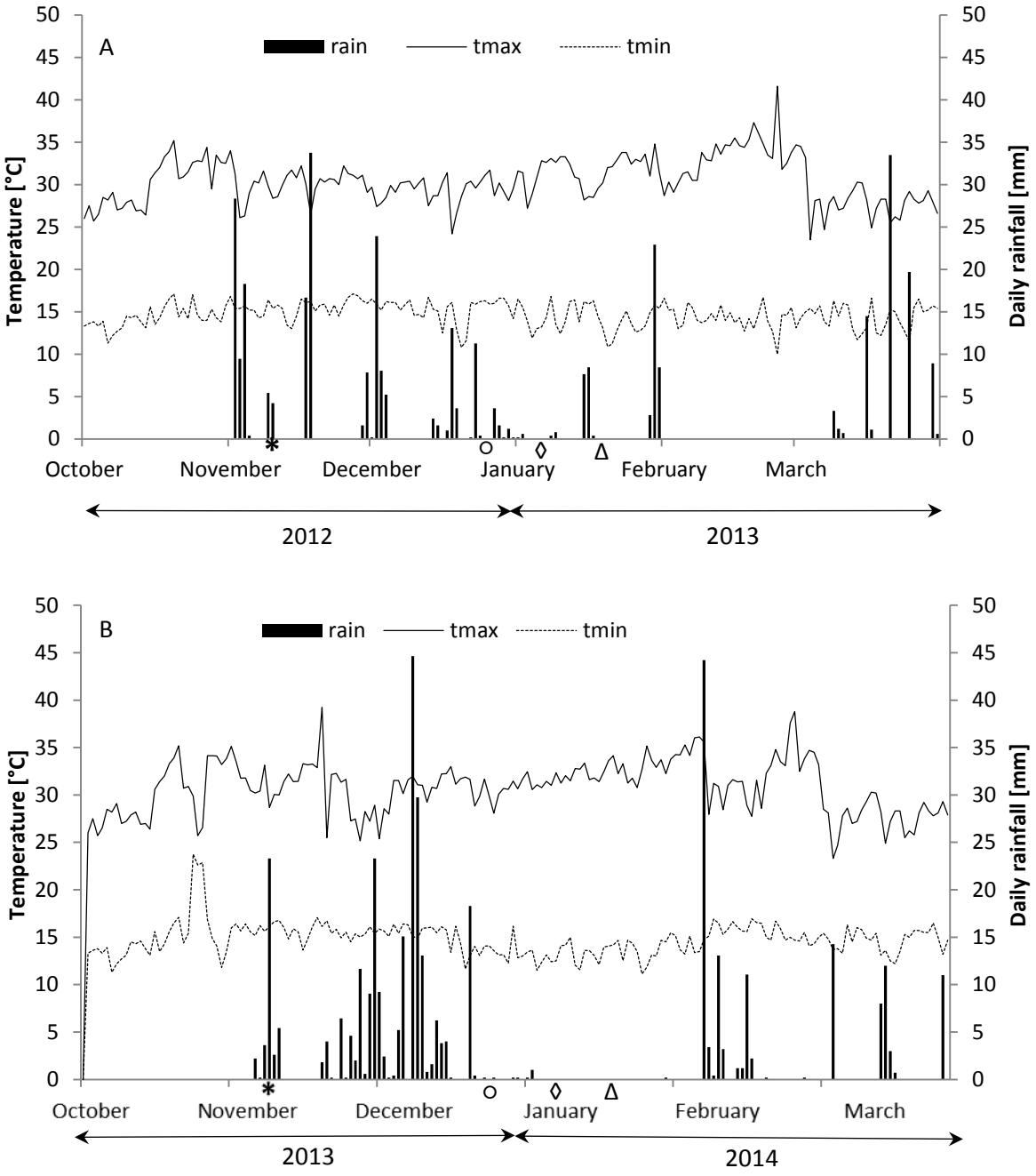

Figure 9: Daily minimum and maximum temperatures, and rainfall during the growing periods of the short rains of (A) 2012/13 and (B) 2013/14 at KARI Katumani, Kenya.
* Planting date
○ Common bean harvest
◊ Cowpea harvest
Δ Lablab harvest

Table 5: Irrigation, rainfall, water use (E_t), ratio of pre- and post-anthesis water use (E_{tpr}/E_{tpost}) and water use efficiency for biomass production and grain yield of short-season legume species grown under different water regimes in Machakos, Eastern Kenya during the short rains of 2012/13 and 2013/14.

Season	Species	Water regime	Irrigation [mm]	In-crop rainfall [mm]	Irrigation + rainfall [mm]	E_t [mm]	E_{tpr}/E_{tpost}	Total Biomass at harvest [kg DM ha^{-1}]	Grain yield [kg ha^{-1}]	$WUE_{biomass}$ [kg ha^{-1} mm^{-1}]	WUE_{grain} [kg ha^{-1} mm^{-1}]
2012/13	Bean	fully irrigated	270	156	426	481	2.06	3638	1888	7.6	3.9
		partly irrigated	150	156	306	361	4.55	2940	1557	8.2	4.3
		rainfed	0	156	156	187	2.13	2182	1107	11.7	5.9
	Cowpea	fully irrigated	300	190	490	578	4.73	5629	3061	9.7	5.3
		partly irrigated	225	190	415	493	14.70	4068	1968	8.3	4.0
		rainfed	0	190	190	277	3.71	2574	1385	9.3	5.0
	Lablab	fully irrigated	345	190	535	609	2.47	3652	1933	6.0	3.2
		partly irrigated	210	190	400	453	9.89	2937	1438	6.5	3.2
		rainfed	0	190	190	243	4.90	2966	1234	12.2	5.1
L.S.D. [water treatment: rainfed] P = 0.5								*408*	*245*	*1.9*	*1.1*
2013/14	Bean	fully irrigated	240	259	499	503	1.07	3335	1956	6.6	3.9
		partly irrigated	60	259	319	323	4.10	2628	1460	8.1	4.5
		rainfed	0	259	259	2450	7.22	1762	978	7.2	4.0
	Cowpea	fully irrigated	330	259	589	596	2.64	4487	2210	7.5	3.7
		partly irrigated	180	259	439	443	15.26	3431	1541	7.8	3.6
		rainfed	0	259	259	256	66.39	3030	1512	11.8	5.9
	Lablab	fully irrigated	345	339	684	635	2.15	5474	2352	8.6	3.7
		partly irrigated	180	339	519	470	6.56	3965	1996	8.4	4.2
		rainfed	0	339	339	290	7.77	3906	1873	13.5	6.5
L.S.D. [water treatment: rainfed] P = 0.5								*787*	*367*	*3.0*	*1.4*

L.S.D. – Least Significance Differecence

For the rainfed treatment the accumulated biomass and grain yield were always lowest for common bean. However, biomass and grain yield of common bean was fairly similar for all treatments in both seasons, indicating relative stable yields independent of inseaosn rainfall amount and pattern. Biomass und grain yields for cowpea (grain yield: ~1500 kg ha^{-1}) and lablab (grain yield: 1880 kg ha-1) were higher in the wetter season of 2013/14. In general, grain yields were increased with applied irrigation but to a different extent for the different legumes and seasons. In the growing period of the short rain with above-average rainfall in 2012/13 the yield increase with additional irrigation was very high for cowpea, 130 % from 1400 to 3060 kg $ha^{-}1$ and less pronounced for bean (+70 %) and lablab (+67 %). During the growing period of the short rain of 2013/14, with intensive rainfall from end-November to end-December and a very long dry spell in January, the yield increase with applied irrigation was significant and highest for common bean (+100 %) and less, however, still significant for cowpea (+47 %) and lablab (+26 %). This is an indication of a higher compensation capability of dry spells by cowpea and lablab in comparison to the truly short-season legume common bean. The effect of the partly irrigated treatment was not significant for cowpea and lablab, were yields remained on the rainfed levels due to the heavy rains occurring during the vegetative growth period. The magnitude of the biomass development in respect to water treatment and season was similarly to the ygrain ield accumulation.

The ratio of pre- to post anthesis water use was highly influenced by the phenological development of the legume, the specific rainfall pattern of the season, and the timing of the additional water supply through irrigation. During the short rain of 2013/14, the ratio was very high for the rainfed treatment in comparison to the irrigated water regimes and to the generally drier season of 2012/13. This was caused by extensive rainfall at the end of 2013 - the vegetative growth period of cowpea and lablab and the dry spell in January 2014 during the reproductive growth phase. The water-use efficiency in terms of biomass production and grain yield was always highest without supplementary irrigation, except for cowpea in 2012/13. Under rainfed conditions $WUE_{biomass}$ ranged from 7.2 to 11.7 for common bean, from 9.3 to 11.8 for cowpea, and from 12.2 to 13.5 kg DM ha^{-1} mm^{-1} for lablab. Similar to the trends in biomass and yield development for the short-season common bean, $WUE_{biomass}$ was in higher 2012/13 in comparison to the season of 2012/14, whereas the opposite was true for cowpea and lablab. Similar was observed for the WUE_{grain}. During the comparatively dry growing period of the short rain in 2012/13, WUE_{grain} was highest for common bean (5.9 kg ha^{-1} mm^{-1}) without additional irrigation but not significantly different to cowpea (5.0 kg ha^{-1} mm^{-1}) and lablab (5.1 kg ha^{-1} mm^{-1}). However, in 2013/14, WUE_{grain} was significantly increased for cowpea (5.9 kg ha^{-1} mm^{-1}) and lablab (6.5 kg ha^{-1} mm^{-1}) in comparison to common bean (4.0 kg ha^{-1} mm^{-1}) under rainfed conditions.

Simulation of water use

Phenology

The temporal development of the different legumes varied at three sites, Katumani, Kampi ya Maww and Makindu along the Machakos – Makueni transect. Both species and the site had a significant impact on days to flowering, which was shortest for common bean (32-37 DAP) at all three sites along the transect, followed by cowpea and lablab (Table 6). At all three sites, time to flowering was not statistically different between cowpea and lablab. Both legumes flowered significantly earlier at the slightly hotter Kampi ya Mawe (57-60 DAP), followed by Makindu (cowpea: 67-69 DAP, lablab: 66-70 DAP) and Katumani (cowpea: 80-84 DAP, lablab: 79-81 DAP). For common bean, the time to flowering was only slightly delayed at comparatively cooler Katumani, but similar for Kampi ya Mawe and Makindu. The growing season had no effect on flowering time. Similar was observed for time to physiological maturity. Common bean (65-73 DAP) matured significantly faster than cowpea and lablab at all three sites, but time to maturity was increased about one week at Katumani in comparison to Kampi ya Mawe and Makindu. Even if flowering was observed as slightly earlier for lablab, time to maturity was shorter for cowpea in comparison to lablab. However, the site had significant impact on the maturity time of both cowpea and lablab. Time to maturity was shortest at the comparatively hot site Kampi ya Mawe (cowpea: 82-88 DAP, lablab: 94-97 DAP), followed by Makindu (cowpea: 97-100 DAP, lablab: 95-112 DAP) and Katumani (cowpea: 114-126 DAP, lablab: 123-143 DAP). There was a trend of delayed maturity for cowpea and lablab during the growing period of the long rain in comparison to the short rain in Makindu and Katumani, however, this was only significant for lablab at Katumani. The differences in phenological development along the Machakos - Makueni transect can be explained by varying temperatures and, consequently, different time needed to accumulate similar heat sums (thermal time, °Cd) to reach certain developmental stages.

Table 6: Simulated days to flowering and physiological maturity in days after planting (DAP) for common bean, cowpea and lablab grown in Katumani, Kampi ya Mawe and Makindu during the growing period of the short rain (SR) and long rain (LR).

	Katumani		Kampi ya Mawe		Makindu	
Species	SR	LR	SR	LR	SR	LR
			Flowering (DAP)			
Bean	37	36	32	35	34	33
Cowpea	80	84	60	57	67	69
Lablab	79	81	60	59	66	70
			Maturity (DAP)			
Bean	73	73	65	67	67	65
Cowpea	114	126	88	82	97	100
Lablab	123	143	97	94	95	112

Grain yield and water use

The agricultural zone in Eastern Kenya is characterized by high inter- and intra-seasonal rainfall variability as described in the previous section. Figure 10 illustrates the relationship between effective in-crop rainfall (rainfall from sowing to maturity minus drainage and runoff) and the simulated grain yield of common bean, cowpea and lablab. For the long-term simulation, the amount of effective in-crop rainfall was scattered from less than 100 mm to almost 500 mm at all three sites within the research area. The response to the amount of effective in-crop rainfall available to the plant, however, largely differed. Common bean was very little responsive to in-crop rainfall and yields were relatively stable but rarely above 1000 kg ha^{-1}. Neither the soil nor the growing period had a significant influence on common bean yield. However, even with effective in-crop rainfall of less than 150 mm, comparatively high potential common bean grain yields were observed. Cowpea, instead, seemed highly responsive to effective in-crop rainfall, and grain yields were largely scattered and significantly increased with the total amount of effective in-crop rainfall. Therefore, cowpea grain yields of 3000 kg ha^{-1} and more were possible in wet seasons with rainfall above 300 mm. In comparison to cowpea, lablab was less responsive to effective in-crop rainfall, but grain yields were generally higher than those observed for common bean. However, it seemed that lablab has species-specific threshold of 3000 kg ha^{-1}, which cannot be exceeded independent of the environmental conditions. Consequently, the slope of yield increase with increased rainfall was less steep than observed for cowpea. At Katumani, simulated lablab grain yields at low levels of effective in-crop rainfall were generally higher in the growing period of the long rain in comparison to the short rain. Lablab might have benefited by a better usage of residual soil moisture from the short rain in comparison to the dry long rain season.

The simulations showed that the amount of soil evaporation and crop transpiration for different soils and sites along the transect was not constant but very variable for all three legumes. In general, soil evaporation, crop transpiration and, consequently, evapotranspiration were lowest for common bean independent of soil and site, caused by the significantly shorter growing period in comparison to cowpea and lablab (Table 7). For that reason, time scales need to be considered carefully when interpretating simulated water use data of the different legumes. But even if the growing period of cowpea was significantly shorter than that of lablab at most sites, crop transpiration was always highest for cowpea (ranging from 58 mm in Makindu to 124 mm in Katumani), caused by the large crop canopy and relatively high biomass. The small and bushy common bean transpired relatively little, between 36 and 51 mm on average, depending mainly on the rainfall zone. The Lablab plant was larger than common bean but the compact growth habit led to relatively low crop transpiration in comparison to cowpea, ranging from about 50 mm at Makindu to about 70 mm in Katumani. The effect of the soil on the crop transpiration was comparatively little; whereas the soil evaporation was always higher on the clay soil (soils with high and medium PAWC) than on the sandy soil (low PAWC), due to rainfall penetrating deeper into the profile on sandy soils, thus, being less prone to loss by evaporation from the surface (Table 7). Soil evaporation was also correlated to the amount of seasonal rainfall. With increasing seasonal rainfall much more water was lost through soil evaporation.

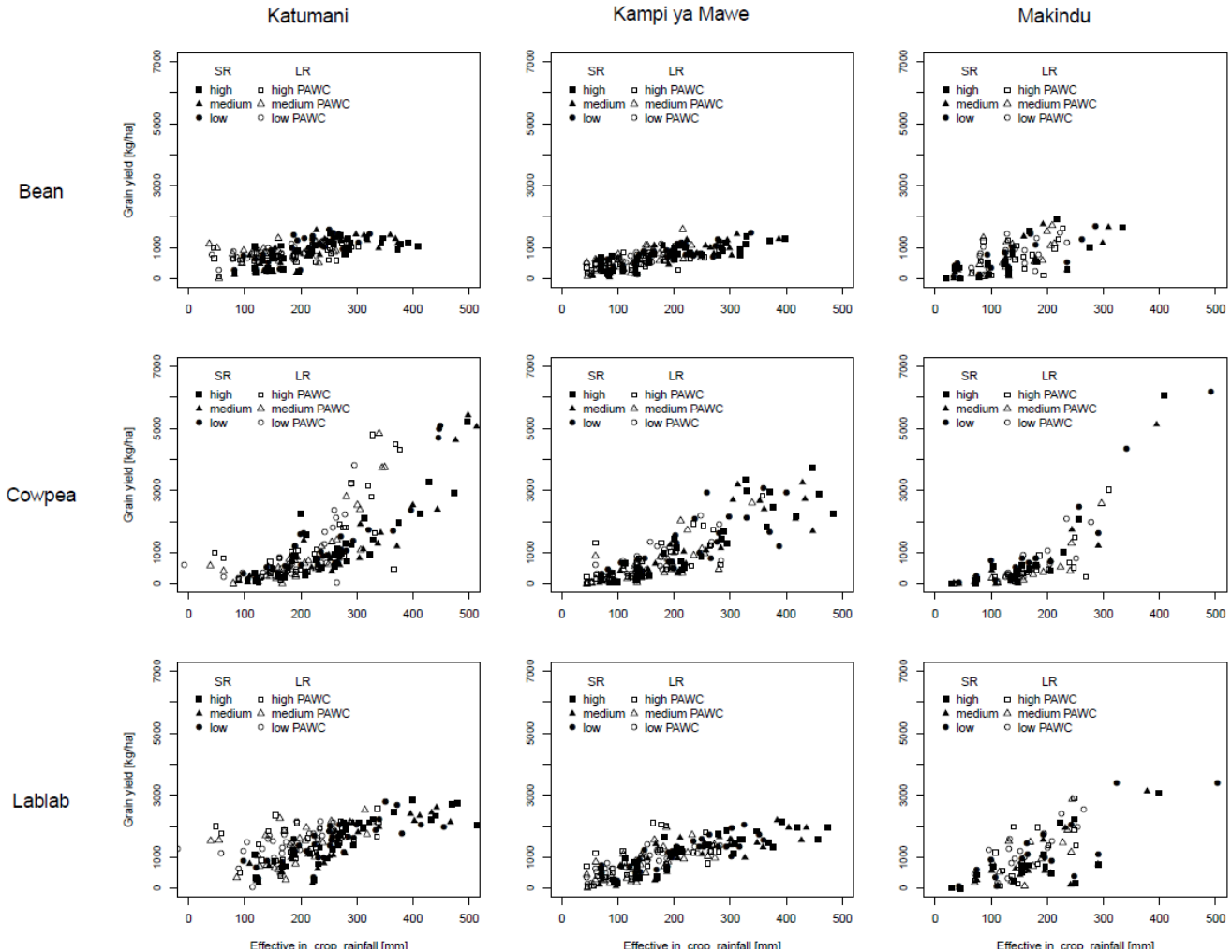

Figure 10: Relationship between simulated legume grain yield kg ha^{-1} (top: common bean, middle: cowpea, bottom: lablab) and effective in-crop rainfall in mm at the high (Katumani, left), medium (Kampi ya Mawe, middle) and low rainfall zone (Makindu, right), simulated for soils with different plant available water capacity (PAWC; high, medium and low) and the growing period of the short rain (SR: October – February) and the long rain (LR: March – June).

Table 7: Simulated long-term average and range (minimum and maximum) of soil evaporation, crop transpiration, and total evapotranspiration for the short rain season (October – February) at Katumani (1981-2013) and Kampi ya Mawe (1981-2012) for common bean, cowpea and lablab grown on soils with different plant water holding capacity (PAWC; high, medium, low).

Site	Species	Soil type PAWC	Soil evaporation (mm)			Crop transpiration (mm)			Evapotranspiration (mm)		
			mean	min	max	mean	min	max	mean	min	max
Katumani	Bean	high	134	51	185	45	3	82	**232**	166	418
		medium	136	53	184	49	1	91	**237**	166	448
		low	124	55	172	49	14	82	**230**	165	370
	Cowpea	high	154	87	208	124	7	299	**321**	196	913
		medium	160	75	216	107	1	305	**336**	202	685
		low	144	85	204	109	3	274	**324**	193	900
	Lablab	high	179	92	276	78	13	138	**382**	209	545
		medium	187	79	280	69	10	129	**396**	212	635
		low	166	90	265	73	3	135	**395**	208	741
Kampi ya Mawe	Bean	high	124	48	191	48	8	119	**241**	162	297
		medium	127	50	187	49	4	141	**249**	162	347
		low	113	41	179	51	8	133	**240**	162	296
	Cowpea	high	131	47	210	93	4	341	**269**	190	382
		medium	136	48	218	78	0	307	**285**	192	495
		low	121	47	205	83	3	277	**269**	188	459
	Lablab	high	143	49	253	66	5	150	**304**	175	493
		medium	148	50	256	58	1	151	**318**	176	512
		low	132	45	227	61	10	142	**308**	174	521

In each mean column values are illustrated with fil color: dark grey represent relatively high values and light grey relatively low values if compared within one column.

This relationship also appeared along the Machakos – Makueni transect from high to low rainfall zone, with the highest soil evapotranspiration in the high rainfall zone Katumani in comparison to the low rainfall zone Makindu. Relatively high biomass production and a good canopy soil coverage, however, reduced soil evaporation as observed for cowpea in comparison to lablab. However, a reduced soil evaporation came along with the investment of an increased crop transpiration. But final evapotranspiration of cowpea was still lower than simulated for lablab, not least because of the shorter growing period.

Simulated median (50 % quartile) of common bean grain yields were almost constant at about 800 kg ha^{-1} at all sites and soils and for both growing periods of the short and the long rain (Figure 11). Only in about 25 % percent of the growing seasons within the last four decades, potential common bean yield exceeded 1000 kg ha^{-1}. The 25 and 75 % percent quartile give a measure of the long-term variability and were only about plus minus 20 – 30 % of the median common bean grain yield and in particular low for simulated yields during the growing period of the long rain in Katumani and Kampi ya Mawe. The site and the soil had relatively little impact on the simulated bean grain yield. In contrast the observed yield variability was very high for cowpea in particular at the high and medium rainfall zones Katumani and Kampi ya Mawe. Here, the inter-quartile range was as high as 1500 kg ha^{-1} for the soil with a high PAWC and about 1000 kg ha^{-1} for soils with medium to low PAWC, correlated with the high intra-seasonal rainfall variability at these sites. Surprisingly, the probability of cowpea grain yields to exceed 1000 kg ha^{-1} was comparatively to common bean. However, cowpea grain yields were still significantly higher than those of common bean for the growing period of the short rain, whereas in the growing period of the long rain this was not the case. At the low rainfall zone in Makindu, the simulated cowpea grain yield was even lower than that of common bean, caused by relatively high water losses through crop transpiration. During the growing period of the long rain the simulated cowpea yield was also significantly lower than that of lablab, whereas during the short rain they were not statistically different. Even if lablab grain yields did not reach extreme values of above 3000 kg ha^{-1}, the simulated median yields were always highest in comparison to the other legumes. In particular, at the low rainfall zone Makindu during the growing period of the long rain there were still a 50 % probability that lablab yields are above 1000 kg ha^{-1}.

Even if the soil had no significant impact on the simulated legume grain yield at each individual site, a larger variation in cowpea and lablab grain yield was observed on clay soils (high PAWC) at the high and medium rainfall zones, indicating higher yields in the wetter seasons but also a greater risk of yield failure in drier seasons. At the low rainfall zone Makindu, median cowpea and lablab yields were slightly higher on the sandy soil (low PAWC) instead indicating a better availability of the scarce water on these soils in low potential areas. The effect of pre-season water storage on PAWC during the short rain season is negligible as the soils in semi-arid Eastern Kenya are usally completely dried out after the long dry period from July to October.

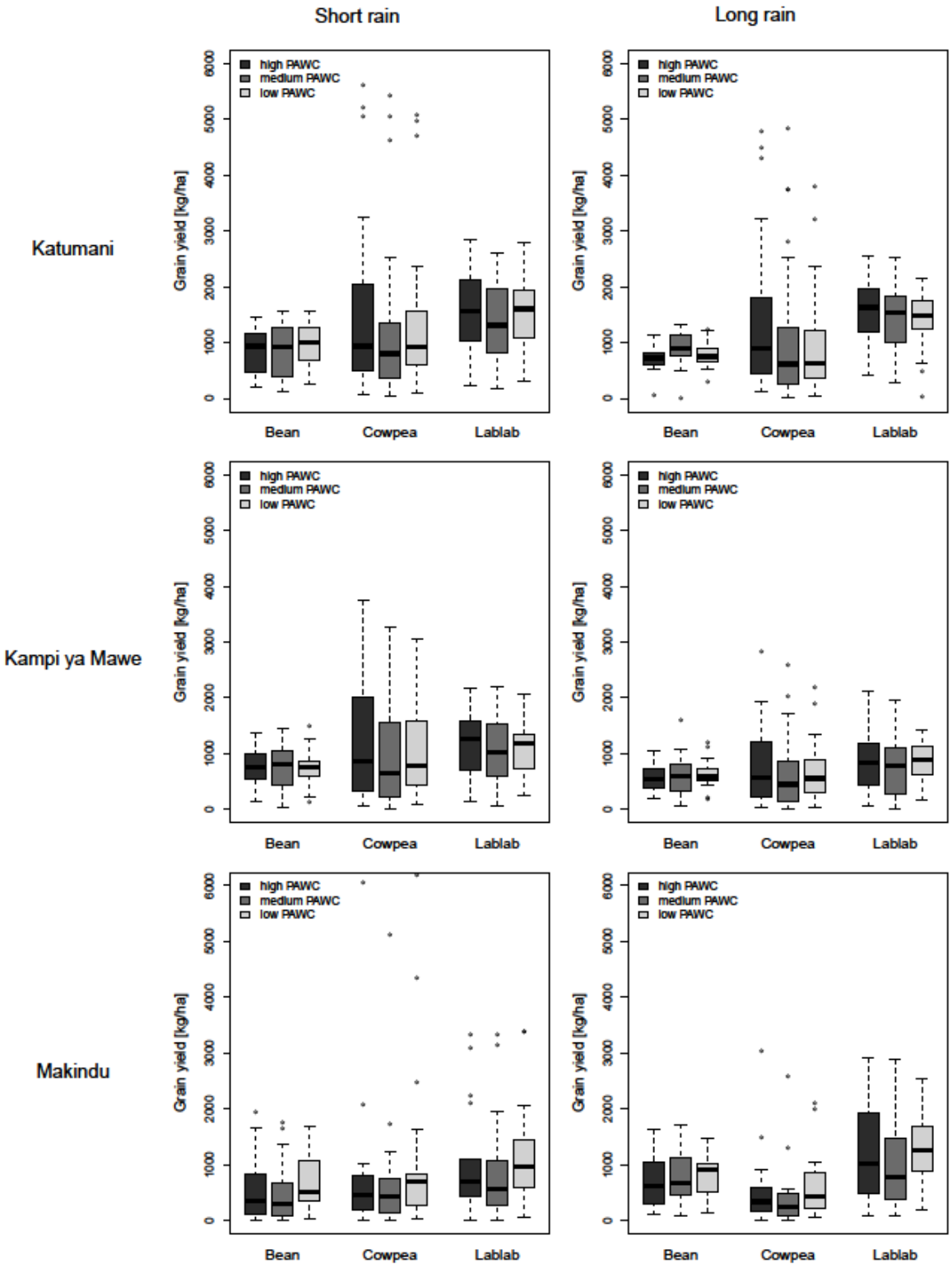

Figure 11: Boxplots of simulated grain yields for common bean, cowpea and lablab at different rainfall zones (Katumani, Kampi ya Mawe and Makindu, Eastern Kenya) grown during the growing period of the short rain and the long rain on soils with different plant available water capacity (PAWC, high, medium and low) based on results from the long-term simulation as described in the material and methods.

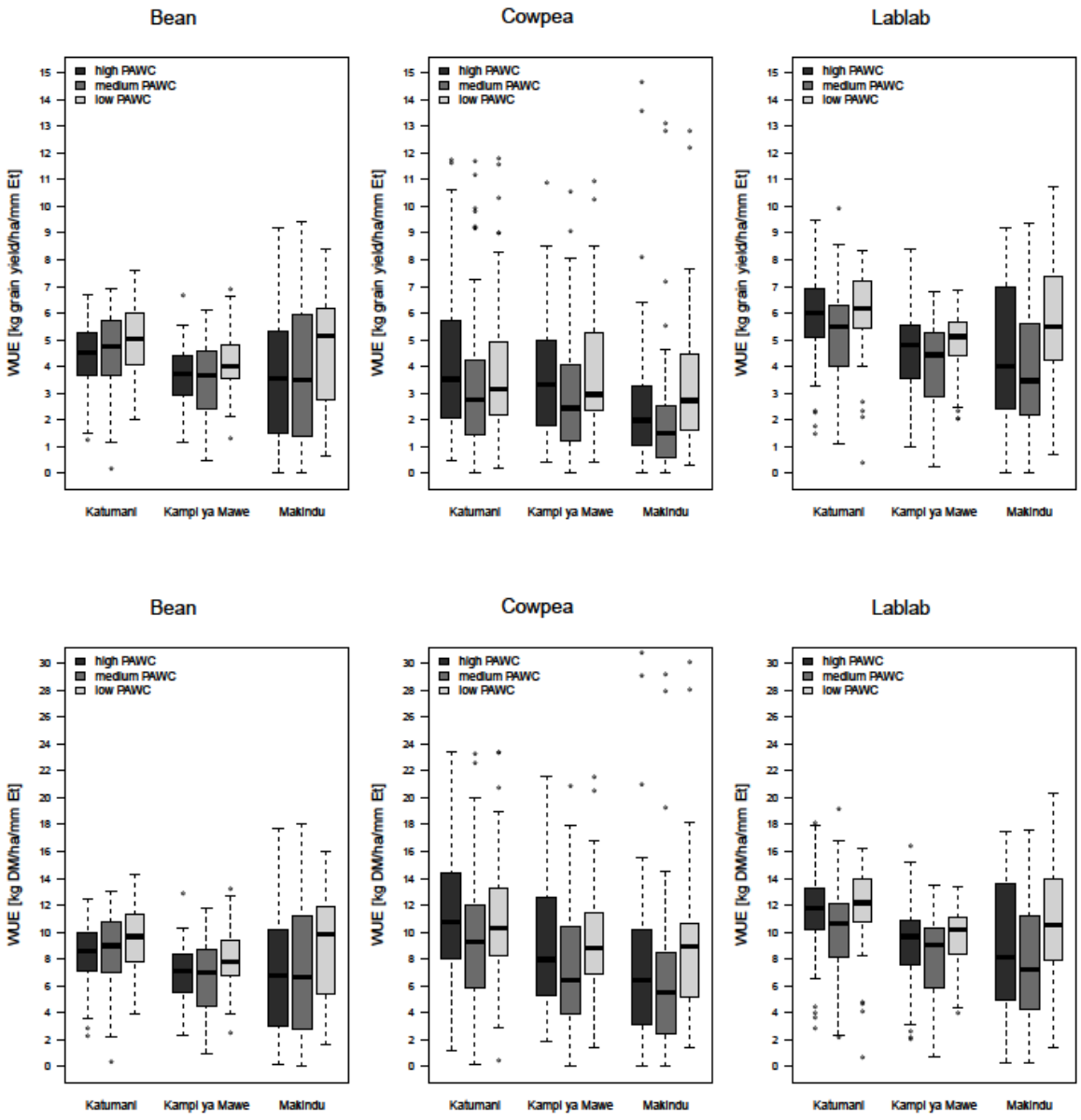

Figure 12: Boxplots of simulated long-term average water-use efficiency (top: kg grain yield ha^{-1} mm^{-1} E_t; bottom: kg DM biomass ha^{-1} mm^{-1} E_t) for common bean, cowpea and lablab at different rainfall regions (Katumani, Kampi ya Mawe and Makindu) for different soils (high plant available water capacity (PAWC), medium PAWC, low PAWC).

Water-use efficiency

Simulated long-term average water-use efficiency in terms of biomass production and grain yield varied significantly among the legume species, sites and soils. The WUE_{grain} however, was not statistically different for common bean, cowpea and lablab at the medium and low rainfall zones Kampi ya Mawe and Makindu. Nevertheless, the median WUE_{grain} was always highest for lablab, but only statistically significant higher at Katumani and always greater than 5 kg ha^{-1} mm^{-1} E_t for all soils. Whereas the average WUE_{grain} of common bean and cowpea ranged from 3 to 4.5 kg ha^{-1} mm^{-1} E_t only and was even below 3 kg ha^{-1} mm^{-1} E_t at the low rainfall site Makindu for cowpea. The water-use efficiency in terms of biomass production was significantly higher for cowpea and lablab (8 - 12 kg ha^{-1} mm^{-1} E_t) in comparison to common bean (6 – 8 kg ha^{-1} mm^{-1} E_t). Moreover, average WUE_{DM} was always higher at the high rainfall site Katumani if compared to the low and medium rainfall sites. The site effect on WUE_{DM} was very clear for cowpea. Furthermore the inter-quartile range was increased from the high to the low rainfall site, particularly for common bean and lablab, indicating an increased variability with decreased seasonal rainfall. Surprisingly, average WUE_{grain} and WUE_{DM} were always higher at the sandy soil with low PAWC in comparison to the clay soil with medium PAWC, in particular at the low rainfall site Makindu, representing a better water availability and allocation of the limited resource at these sites.

Discussion

Climate variability in Eastern Kenya

The results of high season-to-season variation in the amount and distribution of rainfall as well as the tendency of decreased rainfall and increased temperatures in semi-arid Eastern Kenya is in agreement with other studies from the same area (Claessens, 2012; Rao and Okwach, 2005; Kabubo-Mariara and Karanja, 2007). Even if the names are confusing, the short rain seasons receive generally more rain and are known to be more reliable than the long rain season (Karanja, 2006; Rao and Okwach, 2005). Therefore, the growing period of the short rain season is more important for agricultural activities in the area. However, the simulation results indicate that the overall pressure on crop production will be even increased in the future. Various studies show that the amount and temporal distribution of rainfall is the most important determinant of inter-annual fluctuations in crop production, with significant impacts on the country's economy as well as food production and security (Kabubo-Mariara and Karanja, 2007). The magnitude of impact of decreased rainfall and or increased temperatures may vary from low to high potential zones. Studies show for example that crop yields are highly elastic with respect to changes in rainfall (Kabubo-Mariara and Karanja 2007). However, the prospected temperature increase might have a more severe impact on crop production because it can accelerate the crop development and ripening processes. Cooper et al. (2009), for instance, predict that a increase in temperature of 3 °C will cause a mean decline of peanut yield in Zimbabwe of 33 % and pigeon pea yield in Kenya of 19 %, mainly caused by faster and earlier maturity. Availible crop varieties might not be able to exhaust their physiological potential because of the shortened development time aligned with increased stress due to more frequent extreme temperature events (Figure 3). Changes in both, rainfall pattern and temperatures can shift or even shorten traditional growing periods. The length of a growing period and, most importantly, its reliability, however, determine the suitability of a cropping strategy in a certain area, which is a fundamental indicator for site-specific yield potential (Cooper at al., 2009; Recha et al., 2013). Results showed a large inner-annual variability of the growing period length for both short and long rain season (Figure 7). The analysis exhibited a slight trend towards later start, in particular for the growing period of the short rain. Moreover, the onset of the growing period was negatively correlated with the growing season length (Figure 7). Shorter growing periods, however, increase the probability of external droughts and diminish crop productivity. Recha et al. (2013) confirm that many parts of semi-arid Eastern Kenya are likely to experience a decrease in their growing season length, which is one of the most critical factors for rainfed crop production (uncertainty of the growing period start and length), as it requires flexible and adapted management strategies. In Kenya, a reduction in maize yield of 25-30 % was observed due to a 20-day delay of the growing period of the long rain (Camberlin and Okoola, 2003). Moreover, the probability of in growing season dry spells is comparatively high and even increased from the high potential areas in the northwest of Machakos towards the low potential areas in the southeast of Makueni according to the simulation. The probability that crops are exposed to moisture stress within the growing period is serious, in particular, during the growing period of the long rain. In Kampi ya Mawe the chance of a dry spell of 7 days during early growth stages of the short and long rains is about 15 - 20 %, and even higher during late developmental stages with about 40 - 50 % (Figure 8). However, various

studies indicate that in-growing season dry spells and uneven distribution of in-growing period rainfall are one of the major causes of crop failure in semi-arid areas (Passioura and Angus, 2010; Turner et al., 2001). Subbarao et al. (1995), for example, highlight the importance of characterizing drought patterns within a growing period besides the quantitative rainfall analysis to better identify niches for certain crops or cropping strategies in a given environment. The alignment of crop phenology to changes in rainfall pattern is one of the major challenges for rainfed agriculture in semi-arid areas in the future. This will determine the yield potential of that location and the suitability of management practices, maturity length, crop types, and cultivars.

Water-use efficiency of short-season grain legumes – evidence from on-station experiments

The field experiments on water-use efficiency showed no clear trend for the different legumes species. Instead, the results highlighted that the pattern of water use seemed more important in determining final WEU_{DM} and WUE_{yield} than the total water use alone. The limited number of observations from a single site, however, make the interpretation difficult, in particular because of the large variation in the amount and distribution of rainfall between the 2012/13 and 2013/14 growing season (Figure 9) and the distinct phenological development of common bean, cowpea and lablab (Table 2). During the 2012/13 growing period of the short rain, in-season rainfall was relatively evenly distributed, but below long-term average. In 2013/14, total in-season rainfall was about long-term average, but approximately 80 % of the in-season rainfall occurred from end-November to end-December – the vegetative phase of cowpea and lablab and during flowering and start of grain filling of common bean. The dry spell in January 2014 affected cowpea and lablab flowering and the grain filling phase of common bean. Therefore, reduced $WUE_{biomass}$ and WUE_{grain} were observed for common bean in 2013/14 (7.2 and 4.0 kg ha^{-1} mm^{-1}, respectively) in comparison to the 2012/14 season (11.7 and 5.9 kg ha^{-1} mm^{-1}, respectively). For cowpea and lablab instead, it was the other way around and greater values for $WEU_{biomass}$ and WUE_{grain} were reached in the wetter season of 2013/13. Because of their longer growing periods, cowpea and lablab seemed to benefit more from increased in-season rainfall than common bean, further indicating a higher phenological plasticity. Similarly, highly variable WUE was oberserved for short-term ley legumes including lablab (cvv. Highworth and Endurance) across sites and seasons in Southern Queensland, Australia (Bell et al., 2012). $WEU_{biomass}$ of lablab, for instance, ranged from 9 to 30 kg ha^{-1} mm^{-1} indicating a high influence of environmental factors. WUE was, however, generally lower at drier sites presumably because a greater proportion of crop water use was lost as evaporation (Bell et al., 2012).

Large variation in WEU_{DM} and WUE_{grain} between seasons was also recorded in a long-term study on chickpea and lentil grown in Mediterranean environment (Zhang et al., 2000). The authors revealed that WEU_{DM} of chickpea (5.0 -14.2 kg ha^{-1} mm^{-1}) was generally lower in comparison to lentils (9.4 -18.2 kg ha^{-1} mm^{-1}). Even if there are species-specific differences in water use and use efficiency both are highly influenced by in-crop rainfall and rainfall distribution (Zhang et al., 2000). Reported WEU_{DM} and WUE_{grain} under rainfed conditions are, however, comparable to results from Siddique et al. (2001) on grain legumes in low-rainfall Mediterranean-type environments, were

$WUE_{biomass}$ ranged from 15 to about 20 kg ha^{-1} mm^{-1} and WUE_{grain} from 5 to 12 kg ha^{-1} mm^{-1} for chickpea, pea or faba bean among others. Earlier studies from Muchow (1985) reported significant increased WUE_{DM} and WUE_{grain} for lablab with increased water supply ($WUE_{biomass}$: 14.1 and WUE_{grain}: 4.6 kg ha^{-1} mm^{-1}) in comparison to rather dry environments ($WUE_{biomass}$: 9.1 and WUE_{grain}: 2.8 kg ha^{-1} mm^{-1}). The author further observed a reduction in the growth duration of lablab due to water shortage and a markedly shortened grain filing period. This is in accordance with the hypothesis of an increased phenological plasticity of lablab as a strategy to escape water deficit though faster development. For cowpea no impact of water supply on $WUE_{biomass}$ (~10 kg ha^{-1} mm^{-1}) and WUE_{grain} (4 kg ha^{-1} mm^{-1}) was observed. Early-maturing short-season varieties, however, seem to have similar yield potential even in areas with short cropping windows or external droughts (Muchow, 1985). The ratio of pre- to post-anthesis water use was highly influenced by the in-season rainfall pattern and no clear correlation with grain yield could be identified. Other studies, however, report a positive relationship between the post-anthesis water use and the accumulated grain yield for grain legumes (Siddique et al. 2001). Early-flowering species and varieties are able to manipulate the ratio through adapted development patterns in favor of water use after the start of flowering. This could function as an adaption mechanism to terminal drought in semi-arid environments and is a function of the interaction between phenology with temporal water use.

In general, the estimated WUE of the studied legumes was lower than observed for C4 cereal crops such as sorghum or maize because of their better transpiration efficiency in hot and dry environments of semi-arid areas (Bell et al., 2012; Sinclair et a., 1984). Furthermore the investment of biological nitrogen fixation led to the cost of reduced transpiration efficiency of C3 legumes in comparison to C4 cereals, which are provided with a mineral nitrogen source (Sinclair et al., 1984). The WEU_{DM} of forage sorghum in southern Queensland for example was comparatively high ranging from 22 – 47 kg ha^{-1} mm^{-1} (Bell et al., 2012).

Water-use und agricultural potential of short-season grain legumes in semi-arid Eastern Kenya

The purpose of the simulation experiment was to explore soil and climate related production limitations for short-season legume cultivation across the Machakos – Makueni transect in Eastern Kenya. So far, the holistic evaluation of WUE of short-season legumes is limited on the basis of single season or single location results as usually obtained from simple field trials. Therefore, the simulation experiment was conducted widely over both time (e.g. the historical weather records) and space (e.g. location and soil types) to better estimate the potential of the different legumes and determine key factors, which mainly influence their performance. Similar to the field trials, a large seasonal variability of determined WUE in terms of biomass and grain yield production was observed from the simulations. This can be attributed to the effects of both the amount of rainfall and its distribution through the growing period. At high potential sites (Katumani) with comparatively high in-season rainfall and a lower probability of in-season dry spells, the water-use efficiency was generally higher in comparison to low potential sites (Makindu) (Figure 10).

The effect of the soil type was increased with the growing period length of the legume species and showed relatively little impact on WUE of common bean, however, a stronger response was observed for cowpea, for instance. In general, the impact of the soil characteristics on water-use efficiency and grain yield has been reported for many crops and sites (Asseng, 2001; Turner, 1986).

The soil is an important component, simply because soil characteristics influence soil evaporation as well as the drainage and runoff behaviour. On sandy soils for example, in-crop evaporation is lower in comparison to clay or loamy soils because less water is stored in the evaporation-sensitive top layer due to deeper rainfall penetration into the soil profile (Table 7). Disadvantageous, however, is the lower PAWC of coarse-textured soils. At sites with unevenly distributed rainfall throughout the growing period, the crop depends on moisture reservoirs to overcome in-growing period dry spells. Sandy soils can store less water than fine-textured soils, and are therefore, less suitable to function as water reserves to compensate challenging environmental conditions. However, evenly distributed rainfall increases the wetness of the soil, especially the evaporation-sensitive top-layer and, consequently, the overall soil evaporation, in particular during periods of low crop cover. Results from the literature confirm that legumes can lose up to 60 % of evapotranspiration as soil evaporation (Turner et al., 2001; Zhang et al., 2000). The share of water loss through soil evaporation was particularly high for common bean (Table 7), indicating an inadequate surface coverage and the potential of improvement through plant density adjustments. The importance of water loss through soil evaporation, however, decreases with crop development and crop surface coverage and can be substantially influenced by crop growth and management (Table 7). Consequently, in areas were water loss through soil evaporation is a major problem any strategy involving fast canopy closure and early canopy interception will increase the amount of transpiration on evapotranspiration and, thereby, increase yield (Turner et al., 2001). In sandy soils with low PAWC, water loss through drainage is a severe problem, particularly at high rainfall sites (Sadras et al., 2003). Furthermore, the importance of soil texture has an impact on the amount of extractable soil water at sowing. This is more important for the growing season of the long rain, as crop growth can benefit from remaining moisture reservoirs from the short rain in the following long rain season. Whereas on sandy soils, water loss through soil evapoaration is usually lower, in total less water can be stored due to lower PAWC. While the impact of residual soil moisture for the success of plant growth during the onset of the short rain is neglectable, the potential crop growth during the long rain partly depends on the residual soil moisture of the short rain. Further, pore size, mainly determined by the soil texture, is one of the major factors influencing water availability to plants. With limited rainfall, the plant available water is generally higher on sandy soils than on in the fine-textured soils.

Water loss through crop transpiration is mainly determined by crop growth and development. It can be quantified in respect to time under consideration of crop phenology, and in terms of space with focus on crop morphology and physiology. In order to analyze the adaption of crops to cope with moisture deficit two major strategies are crucial. First, drought escape through phenological adaption and, second, dehydration avoidance mainly through morphological or physiological mechanisms (Subbarao et al., 1995).

In Eastern Kenya, areas were growing seasons are short or terminal droughts are common, the match of phenological development with the time of water availability is particularly important (Recha et al., 2013). All three studied legumes followed this strategy of drought escape as they flowered and matured comparatively earlier than commonly grown maize, for instance (Table 6). Common bean flowered already about five weeks after planting and was ready to harvest in 10 weeks or less (Table 6). Consequently, water-potential yield of common bean was relatively stable (1000 kg ha^{-1}), independent of total in-crop rainfall and soil conditions (Figure 10 and Figure 11).

No responsiveness to increased water availability was observed and even at the low potential site Makindu or at soils with low PAWC grain yields were not significantly reduced. Many studies on legumes prove that short-duration genotypes have higher and more stable yields than longer duration types (Turner et al., 2001; Vadez et al., 2012). Matching phenological development with water supply is indeed the first way to improve water-limited yields and a successful drought escape strategy (Cooper et al., 2009; Turner et al., 2001). Accordingly, the alignment of crop phenology with predicted site-specific moisture patterns seems to be crucial for the success of rainfed agriculture in semi-arid areas including Eastern Kenya. However, the earliness decreases the overall yield potential of common bean as the fast development is basically a compromise between the accumulation of sufficient biomass without the risk of reducing soil water to a level that will limit reproductive growth. This is a rather conservative strategy, but might be advantageous in challenging environments.

The later flowering time of cowpea, instead, allowed for an increased investment into pre-anthesis biomass accumulation (chapter II), thus, making the crop more susceptible to in-crop dry spells, but allowing to exploit the full yield potential under satisfying post-anthesis water supply. Further it is hypothesized that very-early-maturing genotypes generally invest less in the development of a profound root body, simply because of the lack in time. Consequently, it can be assumed that rooting depth and biomass of common bean is lower in comparison to cowpea. Therefore, short-season varieties, in particular common bean might be more susceptible to intermediate dry spells. Many studies have proved that rooting depth and root biomass of legumes was positively correlated with final grain yield as it allows better water capture (common bean: White and Castillo, 1990; peanut: Wright et al., 1991, among others). Nevertheless, considerable genotypic diversity exists regarding root development and rooting depth, which cannot be predicted from plant development time alone (Turner et al., 2001). Screening for improved rooting characteristics under field conditions is, however, extremely difficult and further research is required on short-season grain legumes.

Besides the match of phenology with water availability, crops have evolved other mechanism to survive in water-limited environments. One is the minimization of water loss through soil evaporation and crop transpiration through the control of growth in space. The bigger the canopy surface cover, the higher the interception of radiation and, consequently, the lower the soil evaporation beneath the canopy. The reduced soil evaporation, however, comes with the cost of an increased crop transpiration (Table 7). This is obvious as in wet years cowpea yield was very high (3000 kg ha^{-1}), whereas in drier years grain yields (>500 kg ha^{-1}) were even lower than common bean grain yields (Figure 10).

The high biomass development of cowpea is a risky investment in areas where in-season dry spells are common, but advantageous in wet years or at high potential sites.

Furthermore, characteristic for short-season legumes is the ability to drop up to 50 % of their leaves to compensate for an increased transpiration demand with increasing temperatures, and/ or decreased water availability without severe yield losses (Subbarao et al., 1995) as leaf nitrogen from senescenced leaves is translocated towards the pods and used to accumulate grain nitrogen (Sanetra et al., 1998). This feature provides legumes an advantage in comparison to other commonly grown cereal crops like maize. Another mechanism to avoid water loss through transpiration is leaf angle change (paraheliotropism).

In particular for lablab, a diurnal change of the leaf orientation was observed in the field, indicating some optimisation ability between radiation interception and dehydration avoidance. Pastenes et al. (2004) proved that paraheliotropism can help to minimize water loss and heat stress in common bean (Pastenes et al., 2004). In general, lablab seemed to be best adapted to dry environments as the grain yield remained comparatively high even at the low potential site Makindu and in years with below-average rainfall (Figure 11). Another advantageous feature contributing to this improved drought tolerance might be the hairy leaf surface of lablab in comparison to the smooth and dark green leaves of cowpea. Whitish hairy leaves reflect more light, reduce leaf surface temperature and, consequently, crop transpiration (Subbarao et al., 1995). Therefore, lablab could continue growing for a longer period into drought than cowpea, for example, and achieved higher yields with less rainfall (Figure 10).

In summary, pronounced spatial and temporal differences in water use and use efficiency of the studied legumes were observed, driven by various phenological, morphological and physiological mechanisms. The ability of the legumes to respond to environmental conditions and the degree of phenological plasticity have evolved different strategies to cope with challenging conditions in semi-arid areas. Furthermore, water-use efficiency is indeed a powerful indicator to estimate the production potential within different environments. However, to answer the question, whether higher water-use efficiency automatically leads to higher yields in water-limited environments is still challenging (Vadez et al., 2012). For groundnut, it was proved that higher levels of WUE lead to higher yields under stress conditions (Ratnakumar et al., 2009; Wright et al., 1994). Blum (2009) however, postulated that the most important determinate of crop production with limited water supply is not high WUE per se, but rather the effective water use. The author highlights, that it is a general misunderstanding that improved WUE is used as synonym for drought resistance and high yield potential under drought stress (Blum, 2005). In the present study the highest WUE in terms of biomass and grain production across sites and soils was observed for lablab (Figure12). Lablab was further the crop with the highest mean grain production, even at the low rainfall site Makindu. Therefore, WUE can be used as an indicator to estimate the yield potential of legumes. The large variation of WUE, however, indicates a big potential for improvement. The impact of in-season dry spells on the growth and development cannot be easily estimated from WUE alone, and characterization of drought patterns are important to identify target environments suitable for crop production (Subbarao et al., 1995). Sadras and Rodriguez (2007), for instance, demonstrate the strong impact of rainfall patterns (events and intensity) on WUE in wheat.

The authors emphasized, that soil evaporation was largely independent of rainfall amount, but tightly related to the distribution and intensity of rainfall events (Sadras and Rodriguez, 2007).

Beyond climatic conditions and soil properties, the water-limited yield potential of legumes can be affected by crop management (Siddique et al., 2012). In order to increase the crop productivity in rainfed farming systems, specific management interventions can help to regulate water use and water losses. Among others, the timing of sowing, the adaption of plant density or mulching techniques have significant impacts on legume production in semi-arid areas (Siddique et al., 2012; Turner et al., 2001). Further, pre-crop management through fallow and different tillage systems has been reported to significantly influence crop water use (Kirkegaard and Hunt, 2010).

Finally, using long-term historical weather records enabled probabilistic interpretation of water-limited potential yield and water use and use efficiency in relation to a range of factors and weather scenarios, not possible through field experiments alone. Crop models, such as APSIM, allow to account for necessary complexity, but at the same time manage to address high location specifity (Turner et al., 2001; Whitbread et al., 2010). This is particular important in diverse smallholder farming systems in semi-arid areas to adequately address their individual needs and opportunities. Furthermore, crop models can be used to intensively evaluate the impact of different management interventions on crop performance and productivity. Through site-specific simulations, it can easily be assessed whether crop phenology matches site-specific environmental conditions (Turner et al., 2001). Moreover, crop models can give evidence whether short-season varieties of legumes are really advantageous for a certain cropping area. The present results highlighted the importance of defining target environments under consideration of the individual potential and specific characteristics beneficial for improved adaption.

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General discussion

Food production in the developing world needs to be doubled if we aim to meet the predicted increased demand for food within the next years (Goldfray et al., 2010). However, this challenge seems even more daunting considering the combined effects of climate change and increased competition for land, water and energy. Sub-Saharan Africa is particularly vulnerable as both supply and demand constraints put additional pressure on already fragile food production systems (Pretty et al., 2011). With this in mind, sustainable intensification of land use is a promising attempt to meet Africa´s food and natural resource needs (Garnett et al., 2013; Keating et al., 2010). This concept sets out to grow more with less, meaning to ´intensify food production while ensuring the natural resource base on which agriculture depends is sustained, and indeed improved, for future generations` (The Montpellier Panel, 2013). Similar is captured in the concept of eco-efficiency, which simply means the output to input relation relative to ecological resources including land, water, nutrients, energy or biological diversity (Keating et al., 2010). On-farm evaluations have, in fact, proven that farm practices that conserve resources improve the provision of environmental services and increase productivity. Findings from a review on agricultural development projects demonstrate that interventions, including more efficient use of water, limited pesticide use and enhancements in soil health, have increased yields by 79 % in more than 50 low-income countries (Piesse and Thirtle, 2010). Other comparative studies have shown that agricultural systems, aiming to conserve ecosystem services by using crop diversification strategies that include legume intensification as well as soil fertility promoting practices (e.g. conservation tillage), perform similar or even better than high-input systems (Pretty et al., 2011). ´The paradox of the scale` describes the phenomena that small diversified farms are able to produce more per hectare land than large monocultures (Tscharntke et al., 2012). Consequently, sustainable intensification aims to increase eco-efficiency and does not only intend to increase productivity. Thereby it offers a risk management strategy by bringing multiple benefits for the farmer and the environment; this is particular important for small-scale and subsistence farmers in semi-arid areas of Eastern Africa including Eastern Kenya (Garnett et al., 2013).

The concept of resource use and use efficiency - what are the opportunities in the context of farming system analysis?

Within the context of sustainable intensification, legume technology is promoted as part of soil health interventions to decrease the need for inorganic fertilizer use. In order to evaluate strategies for sustainable intensification, it is essential to better understand resource use and use efficiencies in agricultural systems. Therefore, it is necessary to reduce the complexity of factors, which determine crop growth and development. To separate effects of environmental factors was first attempted by Monteith et al. (1983). Monteith`s resource capture concept laid the basis for the interpretation of experimental results and aimed to better explore genotype x environment interactions. First, they were able to demonstrate that accumulated biomass production is linearly related to intercepted solar radiation (Monteith, 1972). Secondly, the authors introduced the concept of thermal time to describe the impact of temperature on crop development (chapter II). Monteith`s general principles of resource ´capture` and ´conversion efficiency` for light can also be applied to the relation of produced dry matter per water captured and the efficiency with which it was used (Black and Ong, 2000). As water is the single most limiting factor for agricultural production in semi-arid areas, the quantification of crop water use and water use efficiency is of crucial importance to develop strategies for sustainable intensification in these areas. All three concepts are major components of crop growth models. Within APSIM, thermal time is used to model phenological development, and biomass accumulation is simulated from the radiation extinction coefficient and the crop`s radiation use efficiency (chapter III). Moreover, all three are linked as the daily biomass increase within APSIM is calculated from crop growth rates, first, determined by intercepted radiation, limited by temperature and second, by soil water supply (Robertson et al., 2002). Therefore, the quantification of resource use and use efficiency (chapter II) is not only important to evaluate genotype x environment interactions and design strategies for sustainable intensification, but it is also essential for model calibration and validation purposes (chapter III). The functional relationships and measures of source capacity can further be used to evaluate genetic adaption and suitability e.g. drought adaptability (Passioura and Angus, 2010). However, the complexity of temporal and spatial interactions and the interactive nature of different production functions complicate the interpretation of physiological measures such as RUE and WUE. Furthermore, both are influenced by genetic and environmental factors. Consequently, comparisons within and between species are difficult. Determined RUE (in respect to photosynthetic processes) indicate that C4 species (e.g. maize: 2.5 – 3.7 g MJ^{-1}) reach higher RUE than C3 species, especially in semi-arid areas (e.g. wheat and

legumes: 1.0 – 1.7 g MJ^{-1}), and within C3 species non-leguminous C3 species (e.g. wheat: 1.5 g MJ^{-1}) reach higher RUE than leguminous species (1 g MJ^{-1}) (genetic determinates) (Black and Ong, 2000; Lindquist et al., 2005). This is because C4 species are usually better adapted to hot and dry environments as they are able to maintain higher photosynthesis rates, even under water-limited conditions, through the adapted C4 photosynthesis cycle. The variation observed from experimental results is further caused by a fluctuation of factors such as the atmospheric saturation deficit among many other environmental drivers (Passioura and Angus, 2010; Turner et al., 2001). Similar to studies on maize, where RUE decreased with increased drought stress (Barker et al., 2005; Manderscheid et al., 2014), a reduction of RUE with reduced water availability was observed for short-season grain legumes, in particular common bean and cowpea within this study (chapter II). This is because drought reduces biomass production mainly driven by less intercepted radiation and a decline in the RUE due to stomatal closure and reduced gas exchange (Barker et al., 2005). These findings further highlight the close interaction between phenological, morphological and physiological mechanisms. Observed variation in determined WUE among species and environments was even higher compared to RUE (chapter IV). One reason for this is that, not only genetic and environmental determinants can differ, but also methodology, including measurement techniques, principles and strategies, as well as applied theoretical concepts (Rana and Katerji, 2000). WUE is often quantified as biomass or grain produced per unit water (water use, in-crop rainfall or evapotranspiration). In agricultural systems, water use can be measured as evapotranspiration (E_t.). There is, however, a great variety of methods to measure or predict E_t. Methods include hydrological approaches (soil water balance and lysimeter measurements), micro-meteorological approaches (e.g. aerodynamic method) and plant physiology approaches (e.g. sap flow methods) (Rana and Katerji, 2000). Statistical approaches estimate E_t with the help of models, such as the Pennman-Monteith model (Allen at al., 1989). All methods have their advantages and disadvantages and follow different research intentions. Furthermore, resource use and use efficiency can be expressed at different scales from cellular levels over leaf to plant and field or farm scales. Transpiration efficiency, for instance, is equivalent to WUE at leaf level (Blum, 2009). Comparable to RUE, genotypic and environmental effects on WUE have been demonstrated in various studies on legumes (Siddique et al., 2012). The variation in determined WUE for grain production of chickpea over a range of growing seasons in Syria, for instance, ranged from 1.9 to 5.5 kg ha^{-1} mm^{-1} (Siddique et al., 2001).

Similar high variations in determined WUE were observed across two seasons for common bean (3.9 – 5.9 kg ha^{-1} mm^{-1}), cowpea (3.6 – 5.9 kg ha^{-1} mm^{-1}) and lablab (3.2 – 6.5 kg ha^{-1} mm^{-1}) in Eastern Kenya (chapter IV). Simulation studies further proved the influence of soil water holding characteristics on determined WUE (chapter IV). However, agronomic interventions such as sowing time adjustments and water harvesting techniques have a greater impact on WUE (Turner, 2004; Turner and Asseng, 2005).

Even if applied research in crop production aims to reduce the complexity of resource use to better determine crop growth and development (chapter I and II) by developing functional relationships, the complexity still remains part of the underlying nature. However, the use of natural resources has always been central in agricultural practice. The quantification and improvement of resource use and use efficiencies is, therefore, the major interest of agricultural research and extension. The concept of eco-efficiency simply summarizes the input output relation in respect to ecological resources (land, water, nutrients, energy, etc.) (Keating et al., 2010). The simplest measure remains yield per unit land. Nevertheless, other efficiency measures, which have been discussed above (i.e. WUE and RUE) are crucial to describe agricultural systems at the same time (+ nutrient and labour use efficiency). Even if most of these indices represent simple ratios of output per input in respect to certain resources, they can be defined by a number of different ways as highlighted for WUE above and in, more detail, in chapter IV. This adds to the complexity if systems should be compared by the means of resource measures as demonstrated above. Moreover, the concept of resource use efficiency or eco-efficiency, which applies to agricultural systems, is determined by multiple factors that interact on growth and development mechanisms in both nonlinear and nonadditive means (Keating et al., 2010). The underlying nature of the interaction of resource use determining factors is, therefore, considered in various production response curves. De Wit (1992), for instance, assumed that a higher input efficiency would also reduce the risk of environmental pollution, increase production and profitability and, consequently, increase system sustainability. He further postulated that resources are used optimal when others are close to their maxima too, highlighting the possibilities of synergies of different factors within agricultural systems (de Wit, 1992). Besides the multidimensional character of resource use, its relevance in time and space adds to the complexity of examining interrelationships and trade-offs. Moreover, farming system eco-efficiency can vary with time and eco-efficiency as such can be measured at different scales, including cellular, crop, farm, regional and global levels (Keating et al., 2010).

In summary, over the past decades agricultural research has managed to define and quantify possible yield-determining factors through reductionist approaches and enhance our understanding of resource capture and flow in agricultural systems (Siddique et al., 2012). To design innovative systems many dimensions have to be considered. To rank crops or to evaluate their suitability for a certain environment or cropping strategy, only on the basis of physiological indices is, therefore, very difficult as their usually target different scales. RUE and WUE, for instance, are resource use measures at crop scale, and experimental results, in particular from non-controlled field studies always, belong in the context of their origin and research question. Upscaling or generalization of field-based results is, therefore, restricted and has to be taken with caution. Nevertheless, knowledge derived from these studies needs to be incorporated into a crop management practice to channel agricultural interventions towards increased resource use efficiency and sustainability. Nevertheless, in order to describe a system, people always aimed to understand the underlying principles first. Finally, only quantification of resource use and use efficiencies allow objective evaluation of certain crops or cropping strategies and may proceed towards increased eco-efficiency and sustainable intensification.

How do short-season grain legumes contribute to more productive and resilient farming systems in semi-arid Eastern Kenya?

Legumes are highly valued components in smallholder farming systems as they combine multiple benefits for the farmer and the farming system. One of the major advantage, in particular of grain legumes, is the positive contribution to food and nutrition security. Legumes are the 2nd most import source of human and animal nutrition (Bhat and Karim, 2009). Furthermore, legumes have been emphasized as an effective substitute to animal protein as well as being cost effective (Graham and Vance, 2003) and, in particular, under subsistence conditions, legumes account for more than 50 % of the dietary protein (Vance et al., 2000). Legumes contribute to the diversification of cereal-based diets and are high in vitamins and essential elements, which are usually supplied in low levels in cereals (Siddique et al., 2012). Therefore, an increased cultivation of grain legumes including common bean, cowpea and lablab has the potential to contribute to increased food and nutrition security in Eastern Kenya with positive impacts on human health, in particular under subsistence conditions.

One of the major reasons why legumes are promoted for sustainable intensification, is their ability to fix atmospheric nitrogen - a “free” environmental service – delivering N to be used by the host or associated/ subsequent crops (Graham and Vance, 2003). If legumes are well integrated into the cropping system they contribute to increased N availability within the system through additions of fixed N to the soil N pool and the prevention of N depletion through their N self-sufficiency (Siddique et al., 2012). Consequently, legumes contribute to the positive N balance in cropping systems and add to the overall sustainability and resilience of the whole farming system (Siddique et al., 2001). The integration of common bean in the maize-based farming systems of Eastern Kenya through enhanced inter-cropping technologies has shown to increase the N balance for instance (Maingi et al., 2001). Most importantly, legumes contribute to below-ground N, as legume cultivation increases N availability to associated or subsequent crops (Tittonell et al., 2006), particularly in deeper soil layers where the soil moisture levels are usually higher (Siddique et al., 2001). A wide range of N fixation performance has, however, been reported in the literature. Studies from Western Kenya demonstrate that the mean N_2 fixation of legumes is largely varying with soil and environmental conditions (Tittonell et al., 2005; Tittonell et al., 2006). The greatest resilience in N_2 fixation and net N input across a range of environments and soil fertility gradients was found for lablab and groundnut (Ojiem et al., 2007). For grain legumes, the general N fixation rate is estimated to be about 1 to 2 kg N ha^{-1} per growing season day (Giller, 2001). Therefore, the amount of N fixed per growing season and its potential to contribute to soil fertility varies with maturity time of the crop (chapter II). Early-maturing common bean was reported to fix about 0 - 125 kg N ha^{-1}, whereas the observed nitrogen fixation potential of cowpea is higher due to its longer growing period (9 - 201 kg N ha^{-1}) depending on soil and environmental conditions (Peoples et al., 1995). Consequently, legumes have the potential for making significant contributions to the N economy and productivity of the smallholder systems through atmospheric N_2-fixation (Ojiem et al., 2007).

Besides their positive impact on overall soil fertility, legumes play an important role in maintaining and improving soil health through the increase of soil organic matter levels (Siddique et al., 2008). Soil organic matter is essential for physical, chemical and biological suitability of soils for agriculture practice (Johnston, 1991). In semi-arid areas, short-season grain legumes (common bean, cowpea and lablab) usually drop almost all of their leaves towards the end of the growing season (chapter II) (Siddique et al., 2008). These usually remain on the field in contrast to maize stover, for instance, which is traditionally removed from the field as animal fodder.

The improvement of the soil structure is a major consequence of the increased organic matter content. This further improves the soil water-holding capacity and increases the diversity and activity of soil microbial biomass (Siddique et al., 2012). Moreover, in studies conducted on common bean and maize inter-cropping systems in Eastern Kenya, an increased soil P availability was observed (Maingi et al., 2001). The increased microbial activity, especially of mycorrhiza, with associated legumes facilitates the release of insoluble nutrients such as P, and making them better available to the plant throughout the soil profile. In summary, as part of a cropping strategy legumes enhance soil fertility and health and reduce the need for external inputs such as inorganic fertilizer, particularly important for subsistence farmers predominant in semi-arid Eastern Kenya. However, the potential of species varies in the different biophysical niches and careful selection is, therefore, needed to optimize agricultural productivity.

In the tropics, options for mixed cropping systems are traditionally very diverse and great diversity in crop arrangements and combinations under varying management can be found in smallholder farming systems of Sub-Saharan Africa including semi-arid Eastern Kenya (Muhammad et al., 2010). The high agro-morphological diversity found in legumes as shown in chapter II for crop phenology and morphology, for instance, contributes to the multiple cropping opportunities. Usually, the combination of crops is determined by the length of growing season and environmental adaption, but typically early- and late-maturing crops are combined to ensure efficient resource utilization during the growing season (Siddique et al., 2008). Therefore, short-season grain legumes are promising components in cereal-based small-scale farming systems as traditional cereal crops, such as maize or sorghum, usually have longer growing periods. However, the beneficial effects of growing (grain) legumes on associated or subsequently sown cereal crops can vary to great extent, depending on environmental factors, soil characteristics and management (e.g. sowing date, weed management) (Siddique et al., 2012). Increases in cereal yields following mono-cropped legumes was reported to range 0.5 - 3 t ha^{-1} with a fertilizer N equivalent for the residual effect of different grain legumes on maize of about 7 – 67 kg ha^{-1} and on sorghum of about 40 - 68 kg ha^{-1} (Peoples and Crasswell, 1992). The better integration of legumes in cereal-based smallholder farming systems not only favours a greater crop diversity, but further increases options for cropping strategies including rotations, inter-cropping or alley cropping. This has generally helped to reduce run off and soil erosion and, consequently, increases the groundwater reserve (Pretty et al., 2011). In semi-arid Eastern Kenya, where soils are highly susceptible to soil erosion in particular in the hilly areas, legume cultivation can therefore contribute to increased water availability and use.

The diversity in growth and development found for common bean, cowpea and lablab offer different options to integrate legumes in cereal-based cropping systems of semi-arid Eastern Kenya (chapter II). Furthermore, differences in crop phenology and morphology have a different impact on overall WUE as determined in chapter IV. Cowpea, for instance, showed the greatest soil surface coverage with a great potential to reduce soil erosion and water loss through soil evaporation.

In general, the better integration of legumes in existing cropping systems would, therefore not only increase the diversity of the system but further function as a risk management strategy by reducing the reliance on only one or a few crops (Nguluu et al., 2014; Siddique et al., 2012). Moreover, grain legumes have more, new, alternative and promising market opportunities in comparison to cereals (Franke et al., 2014). They have usually less input requirements than cereals and reach higher prices at local and international markets (Franke et al., 2014; Siddique et al., 2008). Furthermore, as an integrated pest management practice, legumes can break pest and disease cycles in mono-cropping systems of cereals and, consequently, decrease the use of synthetic pesticide use (Siddique et al., 2008). In summary, integrated legume cultivation contributes to food and nutrition security, soil fertility and health, reduces the need for inorganic fertilizer and pesticides and, therefore, has great potential to boost the sustainable intensification of small-scale farming systems not only in semi-arid Eastern Kenya. To exhaust the promising potential of legumes within agricultural systems, appropriate selection of suitable legumes adapted to the environmental conditions is of crucial importance for their success. The maximum N_2 fixation capacity, for instance, depends on various factors such as soil acidity, P availability and soil moisture (Graham and Vance, 2003). Frequent droughts and generally low levels of P in soils observed for semi-arid Eastern Kenya can limit the overall potential and require adapted management strategies (Maingi et al., 2001). The greater susceptibility to biotic and abiotic stresses of legumes in comparison to cereals leads to generally lower yield potential in comparison to competitive cereal crops (Siddique et al., 2012). One of the major constraints for legume production in the tropics remains the high susceptibility to pest and diseases (Graham and Vance, 2003, Siddique et al., 2012). Biotic constraints of legume cultivation require more research emphasis on seeking better plant resistance and exploring agronomic management options to minimize biotic stress. This highlights the need to increase the availability of resistant or better adapted, quality seed material. Furthermore, legume cultivation is generally more labour-intensive than cereal production as the weed competiveness is usually weaker, which requires a higher labour investment for weeding (Siddique et al., 2012). Finally, the yield potential of legumes is

generally lower in comparison to the more competitive C4 cereals (Maingi et al., 2001). However, agronomic management and innovative technologies adapted to resource-constrained smallholder farming systems can contribute to minimize yield gaps in legume production systems of semi-arid Eastern Kenya (Siddique et al., 2012).

Nevertheless, improvement in legume crop yield has not kept pace with those reached for cereal crops such as wheat or maize (Graham and Vance, 2003). This problem is even worse in the developing world, where unfavourable environmental conditions, degraded soils and resource constraints further limit productivity (Cooper et al., 2008). Impacts of climate change are likely to worsen the problem. Chapter IV demonstrates the challenges aligned with climate change in semi-arid Eastern Kenya, including high inter- and intra-seasonal rainfall variability, more extreme temperature events and great variation in growing period start and length. Among others, improvements and interventions towards increased drought tolerance are perquisites to increase adaption and productivity of legumes in smallholder farming systems of semi-arid areas. In Eastern Kenya, areas where growing seasons are short or terminal droughts are common, matching phenological development with the timing of water availability is particularly important. All three studied legumes follow the strategy of drought escape as they flower and mature comparatively early than commonly grown maize for instance (chapter II). Many studies on legumes prove that short-duration genotypes have higher and more stable yields than longer duration types (Turner et al., 2001; Vadez et al., 2012). Matching phenological development with water supply is indeed the first way to improve water-limited yields and a successful drought escape strategy (Passioura and Angus, 2010; Turner et al., 2001). Accordingly, the alignment of crop phenology with predicted site-specific moisture patterns through the use of adapted short-season varieties with high yield potential seems to be crucial for the success of rainfed agriculture in semi-arid areas (Cooper et al., 2009) including Eastern Kenya (chapter IV). Besides the match of phenology with water availability, crops have evolved other mechanisms to survive in water-limited environments. Short-season legumes are able to drop up to 50 % of their leaves to compensate for an increased transpiration demand with increasing temperatures and/ or decreased water availability. This mechanism enables them to compensate in-season dry spells or extreme temperature events without severe yield losses (Subbarao et al., 1995). Thereby they use leaf nitrogen from senescenced leaves, which is translocated towards the pods, to accumulate grain nitrogen (Sanetra et al. 1998). This feature provides legumes an advantage in comparison to commonly grown cereal crops like maize. Therefore, the selection of short-duration legume species and varieties is promising in environments, where

terminal droughts and variable growing period length are likely. Nevertheless, exclusive selection for short-duration varieties, for example, may also result in a lack of capacity to respond to the additional rainfall in more favourable environments or seasons (Turner et al., 2001). However, insights from the literature and results obtained from field studies in semi-arid Eastern Kenya (chapter II) prove that different legume species have different production potentials, but within their specific genetic endowments, their phenological plasticity is pronounced and the ability to respond to changing environmental conditions is very distinctive (Ayaz et al., 2004). The phenological plasticity observed for short-season grain legumes can function as a risk management strategy to adapt to variable climatic conditions and maximize their production potential with increased uncertainties (chapter II).

Agronomic improvement should accept the implication of phenological plasticity and seek to optimize management practices such as sowing date and sowing density, to more effectively exploit the yield potential and broaden the adaption of existing cultivars (Lawn, 1989). However, tropical grain legumes are known to be photo-thermal sensitive (Lawn, 1989). Seasonal and regional effects on phenology and yield potential can, therefore, be relatively large. The first chapter, therefore, aimed to estimate the photothermal response of promising short-season lablab accessions from field and growth chamber experiments (chapter I). Results demonstrate that the photoperiod sensitivity of the studied lablab accessions was very low and that phenology in the tropics and subtropics was not effected by daylength. Insight into photothermal behaviour of crops is of great interest for farmers and agronomist as reduced photoperiod sensitivity and constantly short growing periods are likely to further contribute to increased productivity through a more synchronous reproductive ontogeny (Lawn, 1989). The genetic yield potential of short-season grain legumes in particular the studied ones is already promising (chapter II) (Table 1). The high HI observed for the short-season legumes (common bean, cowpea and lablab) leads to increased biomass partitioning towards the grain and ensures comparatively high returns despite the relatively short growing period (chapter II). Lawn et al. (1989) confirm that the greatest physiological potential for genetic improvement of tropical grain legumes is not the increase in total biomass but rather the increase of biomass partitioned into the seed.

In summary, short-season legumes (e.g. common bean, cowpea and lablab) have been selected for a variety of morphological, phenological and physiological adaption mechanisms to efficiently use the available resources in the production environment of semi-arid Eastern Kenya. In addition, they offer a great agro-morphological diversity with diverse application possibilities in smallholder farming systems.

Even if their overall yield potential remains below those of competitive cereal crops, such as maize, improvements in grain legume productivity cannot be evaluated in terms of grain yield alone but needs to consider their impact on food and nutrition security as well as soil fertility and health, as mentioned earlier. These improvements will further add to the increased productivity of the overall agricultural system by minimizing risk and the need for internal inputs as well as contributing towards sustainable intensification with an increased eco-efficiency of smallholder farming systems in semi-arid Eastern Kenya.

Crop modelling as a promising tool for farming system management in semi-arid areas?

Within the last decades, the ambition of agricultural research to handle the complexity of farming systems in the context of climate change has favoured the development application of modelling tools. Systemic farming system analysis, with the help of simulation models, has promising potential to contribute answers to the challenge of increasing agricultural production and food security for an ever increasing population, while protecting the environment and maintaining ecosystem services. Crop models are modern instruments, which combine the knowledge of many disciplines including plant physiology and soil science and allow us to proceed with the multi-dimensional analysis of farming systems. These were developed on the basis of fundamental research in agricultural science and decades of field research, and they manage to connect data and knowledge for greater use. Recently, considerable progress has been made in the scope and predictive power of modelling tools (Keating and McCown, 2001) favoured by the development of international programs such as the Agricultural Model Intercomparison and Improvement Project (AgMIP; Rosenzweig et al., 2013).

The major challenge of farming system analysis, in particular, in smallholder farming systems of Sub-Saharan Africa is their dynamic, diverse and heterogeneous nature, which is difficult to capture within simple agronomic experiments alone, often limited by single seasons or site designs (Tittonell, 2011; Tittonell et al., 2005). Smallholder farming systems are characterized by high variability in soils, temporal and spatial resource constraints within a complex socio-ecological environment, further challenged by climate variability and change. Crop models, such as APSIM, allow us to account for necessary complexity, but can, at the same time, be highly location-specific (Turner et al. 2001; Whitbread et al. 2010). Therefore, crop simulation models are complementary tools in addition to field experiments, and can function as innovative decision support tools (Ahmeda and Fayyaz-ul-Hassana, 2011).

This is particularly important for diverse smallholder farming systems in semi-arid areas to adequately address their individual needs and opportunities in order to improve resource use efficiency towards the sustainable intensification of these farming systems. In this context, crop models, such as APSIM, offer great application diversity, as they model biophysical processes as responses to environmental conditions and management interventions. Lately, crop models have been used intensively for yield gap studies (Giller et al., 2006; Tittonell and Giller, 2013), to develop risk management strategies (Keating and Grace, 2002), climate scenario impact analysis (Challinor et al., 2007; Challinor and Wheeler, 2008; White et al., 2011), to evaluate new cropping options (Robertson et al., 2000) or to explore possibilities for the genetic improvement of complex adaptive traits in field crops (Hammer et al., 2010) considering different crop species and environments.

APSIM for instance, was already successfully used for farming system modelling in Southern and Eastern Africa to target intervention strategies in smallholder farming systems (Whitbread et al., 2010). Different studies evaluated the impact of various management interventions such as inter-cropping and rotations of legumes and cereals as well as fertilizer and manure application strategies (Whitbread et al., 2010). Furthermore, site-specific simulations offer the possibility to assess how crop phenology matches site-specific environmental conditions (Turner et al. 2001). Therefore, crop models can show whether short-season varieties of legumes are really advantageous for a certain environment as demonstrated in chapter IV. Furthermore, simulation models manage to capture the risk element inherent to agricultural systems, since it is possible to quantify the uncertainties over factors determining return to agricultural production. Via ex-ante assessment analysis, for instance, it is possible to estimate possible returns of increased investment in farm inputs and the greater exposure to risk. Therefore, simulation models can help to identify innovative farming strategies that increase returns for little risk added (Keating et al., 2010). Simulations can further capture the impact of climate associated risk (chapter IV), the major driver for fluctuations in agricultural production in semi-arid areas, and contribute solutions which have the potential to improve the management of climate variability. Furthermore, crop simulations models offer the possibility to include climate scenarios to predict the impact of climate change on crop production in the future.

In summary, if models are calibrated well for a certain environment and crop cultivar, they can be easily used to upscale experimental results to explore niches for promising short-season grain legume varieties across Eastern Kenya for instance. Quality data is, however, necessary for adequate calibration and validation of the models. This is a

prerequisite for their reliability and application. Detailed agronomic and physiological data for parameterization and validation of certain crops, apart from the major cereals such as wheat, maize and rice, e.g. short-season grain legumes, are largely missing. Moreover, the access to necessary climate data including solar radiation, minimum and maximum temperature as well as rainfall on daily basis is often difficult to obtain, especially for parts of Africa and over long periods. Furthermore, the availability of soil characterization data required to determine site-specific parameters is restricted or labour- and time-intensive to obtain. Moreover, soils in Eastern Africa, including the study area are usually highly heterogeneous. Therefore, studies like these included in the present PhD thesis (chapter II and III) are essential in order to make models work for new cultivars and environments. Detailed field experiments, together with consecutive biomass and yield sampling as well as soil measurements, remain fundamental for adequate model calibration and validation work. The degree of accuracy, however, depends on the research question and scale. APSIM for example, seems to be a good compromise targeting to answer questions relevant to farmers, but at the same time with accessible data required for calibration. In order to improve the resource use efficiency of smallholder farming systems in semi-arid Eastern Kenya, simulation studies and yield gap analysis manage to focus on the level at which farmers make decisions (farm and field scale). Large-scale assessments at global, scale instead, fail to target the variability of these systems and ignore the risk element inherent to them. Plant physiology based models instead, do not manage to capture the whole picture of genotype x environment interactions. For other research questions or stakeholders, however, different approaches and scales might be more suitable. The diversity of models available offer tools for various studies, including a different focus from plant to a global scale, with adjusted levels of complexity to address user-friendliness. The grid of the research question from management to process-orientated determines model choice and scale.

The present study however, proved that APSIM seemed to be a good choice in order to evaluate the impact of management interventions or climate variability on the performance of short-season grain legumes in semi-arid eastern Kenya. However, the application has its limitations as the major constraints for legume cultivation in smallholder farming systems, pests and diseases, as well as weed competition and nutrient deficiency apart from nitrogen, are not yet captured very well within the modelling framework. Moreover, in order to estimate the overall benefit of integrating short-season legumes into smallholder farming systems for the farmer and farming system, other response variables apart from biomass and grain yield need to be assessed, including economic and resource allocation factors. Other than agronomic

potential, their contribution to the overall on-farm soil fertility and food security for instance, as well as the economic and labour requirements for their cultivation need to be considered to evaluate the general impact on farm sustainability. These approaches, however, demand further input parameters and models which proceed beyond field level. Optimization experiments considering environmental services as well as socio-economic factors need to be applied in order to find suitable niches with various perspectives. More empirical data is, however, required in order to move from the plot perspective towards the whole farm level.

The great potential of legumes for smallholder farming systems in semi-arid areas is reflected by the number of research and extension programs, which promote legume technologies and target to better integrate legumes in farming systems of semi-arid Eastern Africa, in particular, in the view of climate change; SIMLESA (Sustainable intensification of Maize-Legumes Systems for Food Security in Eastern and Southern Africa; http://simlesa.cimmyt.org/), CALESA (Adapting agriculture to climate change – Developing promising strategies using analogue location in Eastern and Southern Africa; http://www.calesa-project.net/) and N2Africa (Putting nitrogen fixation to work for smallholder farmers in Africa; http://www.n2africa.org/). Within the N2Africa program, for instance, efforts have been put on qualifying and quantifying benefits of legume production for the smallholder farmers in Malawi using ex-ante assessment analysis via farm-scale simulation models (Franke et al., 2014). The authors tested different scenarios, where legume production was increased to a different extend with various input levels. The whole-farm analysis showed that maize production provided more edible yield and a larger grain return to labour than legume-maize systems (Franke et al., 2014). Legume production was, however, more profitable and has the potential to contribute to the overall farm productivity through biological nitrogen fixation (Franke et al., 2014).

Linking whole-farm modelling with budget analysis tools is one option to proceed beyond plot level to merge the assessment of the multiple benefits of legumes. This strategy, however, requires some simplification of the farming systems. Furthermore, it is still challenging to address all aspects of legume production (agronomic, economic, socio-economic, ecological, etc.) through whole-farm modelling, and studies usually have their specific focus limited to a number of selected aspects. Nevertheless, more whole-farm modelling work as well as additional optimization analysis are required to further quantity and qualify the diverse benefits of the short-season grain legumes for smallholder faming systems in semi-arid Eastern Kenya. However, even if simulation models are able to assess the benefits of certain management and cropping strategies, they fail to predict

the possible adoption by farmers as mainly sociological and ethnological factors contribute to the success or failure of new agricultural interventions. These factors are usually left out in crop production system analysis.

Moreover, if solutions (e.g. policy interventions) to improve eco-efficiency or overall sustainability of smallholder farming systems are outside the plot or farm level, simulation models are likely to miss their possible contribution and importance. At the end most of the research studies available represent only a part of the whole picture. Finally, solutions often are rather a combination of interventions as applied agricultural research, including the present study, aim to extend the basket of suitable possibilities. Nevertheless all efforts, independent of their scale, are important puzzles which hopefully contribute to the overall understanding of farming systems with the aim to increase their sustainability and eco-efficiency to face the challenge of increasing agricultural production and protect natural resources in the view of climate change.

Conclusion

To integrate new germplasm into new environments in order to design more resilient farming systems, the timing of phenological events, such as flowering and maturity is of crucial importance. Crop development, growing period length, as well as the switch from vegetative to the reproductive phase are very important do adjust resource use to the availability of resources, in particular in resource-constrained environments of semi-arid areas. The major finding of the photoperiod study (chapter I) on promising short-season lablab accessions, suitable for farming with shortened growing periods and external droughts, was that photoperiod sensitivity always needs to be analysed as photothermal response rather than strict in respect to either temperature or photoperiod alone. The results proved that below the critical daylength (P_c), or as long as photoperiod requirements were met, the development was dominated by temperature only - within the optimal range, reproductive development was accelerated as temperatures increased. The studied lablab accessions can, therefore, be classified as consistently early-flowering short-day plants (SDP), with a thermal time requirement of about 800 °Cd to flower under daylength conditions of ≤13.5 h and within their optimal temperature regime. The critical photoperiod, P_c above which flowering was delayed, however, decreased with increasing temperatures for most of the studied short-season lablab accessions. The studied accessions are, therefore, suitable for use as short-season grain legumes in tropical and subtropical regions as daylength never exceeds 13 h between latitude 30°N to 30°S; but they need further evaluation for their adaption to and productivity under on-farm conditions.

In order to further assess the suitability of certain crops for different application and estimate their production potential, the analysis of growth and development in respect to resource use is primarily interested to develop strategies for climate smart agricultural practice in semi-arid areas. The study on growth and development of short-season grain legumes (common bean, cowpea and lablab) in semi-arid Eastern Kenya (chapter II) proved that there was considerable diversity and temporal and spatial variability in growth and development of common bean, cowpea and lablab cultivars studied, represented by variations in biomass and grain yield accumulation, LAI, HI, RUE and WUE driven by various phenological, morphological and physiological factors. The ability of the legumes to respond to environmental conditions and the degree of phenological plasticity evolved different strategies to cope with challenging conditions in semi-arid areas. Resource use and use-efficiency were primarily determined, in respect to time, by the distinctive phenological development of the different legumes, and further influenced

by morpho-physiological characteristics, such as plant architecture, growth habit, among others, in respect to space. Moreover, the variability in growth and development was high in the legumes studied. Different species have different production potential, but within their specific genetic endowments, phenological plasticity of legumes was pronounced and the ability to respond to changing environmental conditions was very distinctive, leading to different application possibilities within in the smallholder farming systems of semi-arid Eastern Kenya.

In order to further assess new application possibilities of short-season grain legumes within smallholder farming systems of semiarid Eastern Kenya the parameterization and validation of crop growth models is a prerequisite (chapter III). Cultivar-specific parameters, phenological development, HI, HI_incr, were sufficient to calibrate APSIM for short-season varieties of common bean and cowpea. For lablab, however, the adjustment of parameters beyond the cultivar-specific parameters was necessary to simulate growth and development of a short-season annual grain variety with satisfactory accuracy. The amount of data necessary for model parameterization was manageable, and the prediction of the phenological development of the studied grain legumes was very good. Furthermore, the model reproduced the effect of water availability on biomass accumulation and yield development as well as the response to plant density was overall good. The adjustment of species-specific parameters k, RUE and TE had great impact on biomass and grain yield accumulation, reflecting specific characteristics in growth and development of each legume species. In general, simulation results further determined a good relationship between simulated yield and in-crop rainfall, and underlined the importance of taking a water-limited potential yield into account when management practices are considered. The ability of simulating short-season grain legumes in semi-arid areas is one major achievement of this PhD thesis as the use of these varieties has great potential for smallholder systems. APSIM can now be used to simulate benefits and risk of using such species for the farmer, farming systems and environment. Furthermore, the application of simulation models, such as APSIM, contribute to design site-specific climate smart agricultural cropping strategies under consideration of the individual yield potential of the different legumes. Simulation studies, across the environmental gradient, highlighted the very high seasonal variability in determined biomass and grain yield accumulation. This can be attributed to the effects of both the amount of rainfall and its distribution through the growing period. The impact of soil conditions and management interventions, however, varied to a great extend for the different legumes and potential rainfall zones, adding to the complexity of developing suitable climate smart farming strategies.

Capturing climate risk is one of the major challenges for future farming systems in order to improve productivity and profitability. The analysis of long-term weather data from the Machakos – Makueni transect in semi-arid Eastern Kenya revealed large inter-annual as well as inter- and intra-seasonal variation in rainfall and an increase of extreme temperature events (chapter IV). The studied short-season legumes have, however, a great potential to contribute to the sustainability and resilience of smallholder farming systems in semi-arid areas as they offer a great utilization diversity and phenological plasticity to cushion climatic uncertainties. Lablab, for example, had stable yields even in seasons with below-average rainfall across semi-arid Eastern Kenya. In seasons with external droughts, for instance, the cultivation of common bean was advantageous because of their early-maturing characteristics. Cowpea instead was out-yielding common bean and lablab in good seasons with above-average rainfall. An appropriate climate smart risk manage strategy would, therefore, include a combination of different legumes adapted to site-specific conditions. In order to give clear recommendations for farmers in semi-arid areas of Eastern Kenya of how much of their land should be assigned to legume cultivation in order to maximise their benefits, more empirical data is necessary as well as a better understanding of the compromises between productivity and risk and their response to alternative farming design. Therefore, the focus needs to be extended from the plot scale to a whole-farm level, considering in- and outputs (cash, labour, fertilizer etc.), integrated land and livestock management as well as economic and socio-economic factors (markets, infrastructure, prices, gender, etc.,) and their trade-offs. However, these kind of holistic studies, including whole-farm modelling approaches, require the definition of priorities as it is challenging to address all aspects at the same time, including the maximization of farm productivity and profitability as well as the improvement of eco-efficiency and long-term sustainability. Furthermore, these approaches require comprehensive data for extended model parameterization and validation, which is still difficult to obtain, especially from smallholder farmers. At the end, however, future research efforts need to take a step from the crop and field level toward the farm scale in order to deliver concepts for improved eco-efficiency with legumes in smallholder farming systems of Eastern Kenya.

Summary

Poor agricultural productivity and food security remain challenging problems for the majority of smallholder famers in Sub-Saharan Africa, including semi-arid Eastern Kenya. However, there is a general consensus that there is urgent need to significantly increase food production to meet the growing demand aligned with the continuing population growth. Furthermore, the intensification and stabilization of agricultural productivity of small-scale farming systems in Sub-Saharan Africa holds a key position to contribute to the economic development and reduce poverty. The major driver for declining or stagnating agricultural productivity in many parts of Sub-Saharan Africa, such as semi-arid Eastern Kenya, is the decline in soil fertility. Food production is not keeping pace with rapid population growth, forcing farmers to change their traditional farming systems characterized by shifting cultivation, fallow and the use of animal manure. Land and labour restrictions, as well as an increased limited resource endowment further impose the mainly smallholder farmers to focus on the production of staples, such as maize in Eastern Kenya. The investment in soil fertility management strategies remains low and the change from traditionally diverse farming systems to cereal-based monocultures has further increased the susceptibility of the fragile production systems, in particular, to impacts of climate change and variability. The predicted increase in temperature as well as inter- and intra-seasonal rainfall variability will additionally challenge the largely rainfed smallholder farming systems to sustain their productivity in the future.

The integration of legumes within the farming system has been part of traditional soil fertility management strategies since legumes are able to fix atmospheric nitrogen and yields of cereal crops are generally better if grown in rotation or intercropped with legumes. In particular grain legumes are highly valued components in smallholder farming systems due to their direct contribution to food and nutrition security. Moreover, legumes display a great agro-morphological diversity with great potential for challenging environments. Challenges aligned with climate change, such as increased rainfall variability, and restricted short growing periods, make short-season grain legumes a viable option as their adaption strategy of completing their life cycle before the onset of terminal drought seems to be advantageous for cropping with frequent droughts in semi-arid areas. However, to understand the temporal and spatial resource use and use efficiency of potential short-season grain legumes, especially in respect to light and water, it is of fundamental importance to design strategies for climate smart agriculture in risky environments, including areas of semi-arid Eastern Kenya. Furthermore,

quantifying possible magnitudes of yield increase of different grain legumes can be useful in identifying niches in smallholder farming systems to increase overall farm productivity and sustainability. In order to explore the potential of certain crops and cropping strategies in diverse smallholder farming systems, the development and application of crop growth simulation models proved to be an excellent tool. Since African farming systems are highly heterogeneous and dynamic simulation models manage to address the complexity of these systems which is difficult to address through classical agronomic experiments alone. Simulation models are able to capture interactions between climatic conditions, soil type and nutrient dynamics. One of the most applicable models to better understand the complexities of plant growth in response to the environment has been the Agricultural Production System sIMulator (APSIM) framework, which has been successfully used for numerous farming system analyses in semi-arid areas in the past already.

Against this background the objectives of this PhD thesis were, first, to compare growth and development of three promising short-season grain legumes (common bean, cowpea and lablab) in response to plant density and water regime to evaluate their production potential and resource capture in semi-arid environments (research chapter II). This was undertaken by the implementation and analysis of comprehensive field experiments carried out over two season 2012/13 and 2013/14 in Machakos, Eastern Kenya. Additionally to this comparative study of three legume species, the photo-thermal response of early-flowering lablab types were examined in a more detail from a combination of field experiments in South Africa and controlled environments studies conducted in Göttingen, Germany with the aim to evaluate their potential adaption to (sub)-tropical environments as a climate smart farming practice (chapter I). During the field experiments conducted in Machakos Kenya crop development, biomass and yield accumulations as well as leaf area index (LAI) were measured intensively throughout the growing period to determine import agronomic and physiological parameters, such as biomass partitioning coefficient, harvest index (HI) and radiation use efficiency (RUE) for the short-season legumes common bean, cowpea and lablab (chapter II). The output derived from the field experiments was further used to quantify essential cultivar-specific parameters to better calibrate (and later validate) APSIM to simulate growth and development of short-season grain legumes under semi-arid conditions (chapter III). Finally the agro-climatic conditions and changes as well as associated risk for rainfed crop production along the Machakos-Makueni transect in semi-arid Eastern Kenya was characterized in detail to identify possible niches for short-season grain legumes.

For that purpose growth and development, as well as water use and use efficiency were simulated along the environmental gradient using APSIM (chapter IV).

Within the first research chapter (chapter I) a comprehensive analysis of three datasets derived from field experiments in South Africa (different sites and sowing dates) and growth chamber experiments in Germany with a combination of two temperature and four daylength regimes were analysed to evaluate the response of temperature and photoperiod on flowering time of ten promising short-season lablab accessions (CPI 525313, CPI 52533, CPI 52535, CPI 52535, CPI 52552, CPI 52554, CPI 60795, CPI 81364, CQ 3620, Q 6880B). Hence, knowledge of phenological development and, in particular, time to flowering is crucial information needed for estimating the possible production success of new accessions in new and challenging environments, such as semi-arid Eastern Kenya. Therefore, the photoperiod sensitivity was quantified using the triple-plane rate model of flowering response with time to flowering expressed in thermal time (T_t, °Cd). Additionally, piecewise regression analysis was conducted to estimate the critical photoperiod (P_c) above which time to flowering was delayed significantly. Relatively high variation of time to flowering among and within accessions in days after planting (DAP) was observed, ranging from 60 to 120 DAP depending on the site, sowing date or daylength/temperature regime. Furthermore, a clear positive effect of temperature on growth and development of the tested accessions was found and time to flowering, expressed as thermal time, were relative consistent for the tested accessions, ranging from 600 to 800 °Cd for daylength <13.5 h. Only at daylength of ≥13.5 h and temperatures above 28 °C development towards flowering was delayed significantly for accessions CPI 52513, CPI 52535, CPI 52554 and CPI 60795 with vegetative growth continuing for >110 DAP. The tested lablab accessions are, therefore, considered only weak photoperiod responsive and are classified as short-day plants (SDP). Since daylength does not exceed 13 h between latitude 30°N to 30°S covering the semi-arid tropical regions, these lablab accessions can be recommend for further evaluation of their adaption to, and productivity under, on-farm conditions.

However, not only lablab offers a great potential for farming in semi-arid areas, legumes in general have proved to be a promising option in small-scale farming systems by combining benefits for the farmer, soil and environment. Therefore, effects of plant density and drought on growth and development of three promising short-season grain legumes including common bean, cowpea and lablab were quantified in detail to evaluate their agricultural production potential for semi-arid areas (chapter II).

Two comprehensive field experiments; a plant density trial (three different plant densities; low, medium, high) and a water response trial (three different irrigation level: rainfed, partly irrigated (total 50 mm of water per week with supplementary irrigation till bud formation, i.e., onset of flowers), fully irrigated (total of 50 mm of water per week with supplementary irrigation throughout the growing period) were conducted to quantify the effect of plant density and water availability on canopy development, biomass accumulation and partitioning to evaluate resource use and use-efficiency of the different legumes. Therefore, biomass accumulation, leaf area index (LAI) and fractional radiation interception were measured repeatedly during the growing period while grain yield were measured at maturity. From the data collected, harvest index (HI), biomass partitioning coefficient and radiation use efficiency (RUE) were calculated. It was found that clear differences in temporal and spatial development and growth among the evaluated grain legumes are the major drivers for the observed variance in the fraction of intercepted radiation, biomass accumulation and grain yield. Moreover, the response of RUE to plant density and moisture availability differed among the three legumes. Common bean had a very short growing period (10 weeks), limiting the overall production potential (1000-1900 kg ha^{-1}) under favourable conditions through limited source-sink dynamics in terms of time and space. Nevertheless, the short life cycle and the comparatively high RUE of common bean could be advantageous in environments with very short cropping windows. Cowpea showed a high phenological plasticity and potential to respond to favourable water supply in wet years by out-yielding the other legumes and reaching yields up to 3000 kg ha^{-1} under non water limited conditions. However, leaf development was observed to be sensitive to drought leading to decreased biomass development and consequently yield accumulation. The RUE of both common bean and cowpea was relatively low under rainfed conditions reaching only 0.49 and 0.54 g MJ^{-1}, respectively, but more than doubled with supplementary irrigation. In contrast, lablab displayed stable RUE values (0.76 - 0.92 g MJ^{-1}), and was not affected by limiting water availability, resulting in yields of 1200 to 2350 kg ha^{-1} across all water regimes. Nevertheless the growing period length of lablab was by far the longest (~100 days) compared to common bean and cowpea.

The information revealed from the field experiments conducted in semi-arid Eastern Kenya was used to determine genetic coefficients and site-specific soil characterization to parameterize APISM for short-season legumes and semi-arid conditions (chapter III). The models were validated against data from the plant density and water regime trial conducted for two season (2012/13 and 2013/14) including observed data on soil moisture, phenology, biomass accumulation and yield development.

Further, the adapted APSIM legume models were used in a long-term simulation experiment to evaluate the yield potential of the different short-season legumes under various management practices. The model accuracy to predict flowering time and time of physiological maturity was excellent and with a mean root squares of derivation (RMSD) of 5 days and less. For the different plant density and water regime treatments model predictions of biomass and grain yield were satisfactory reaching RMSD values expressed in % of the observed mean of about 12 for common bean biomass and grain yield and 23.5 and 26.0 and 20.8 and 25.1 for cowpea and lablab biomass and grain yield respectively. A good relationship between simulated yield and in-crop rainfall highlighted the importance of taking a water-limited potential yield into account when management practices are designed.

To further quantify the potential of different short-season grain legumes in semi-arid areas where water is the most limiting factor for agricultural production the fourth research chapter aimed to examine the water use and water-use efficiency of short-season grain legumes along an environmental gradient in semi-arid Eastern Kenya (chapter IV). First, the climate variability along this transect was characterized in great detail including the analysis of annual and seasonal temperature development, inter- and intraseasonal rainfall variability as well as the analysis of the dry spell probability throughout the year. Second, growth and development of the short season grain legumes was simulated along the transect using APISM to assess the overall performance of the short-season legumes at different sites (potential rainfall areas) and evaluate the impact of various soil types to estimate their overall agricultural production potential. The analysis of long-term weather data from the Machakos – Makueni transect in semi-arid Eastern Kenya revealed large inter-annual as well as inter- and intra-seasonal variation in rainfall. Further trends showed that the growing season rainfall slightly decreased within the last decades. A decrease in mean rainfall intensity (rainfall per rain day) was observed for the past years as well. Regarding temperature development a slight increase in mean minimum and maximum temperatures was observed over the last decades, associated with an increase in days with maximum temperatures over 25 °C. Further analysis indicated an increased probability of long dry spells within the growing periods along the Machakos - Makueni transect and highly variable start and length of growing periods - creating a risky production environment. The observed variability of determined WUE of the different short-season grain legumes in terms of dry matter and grain yield production from the long-term simulations can be attributed to the effects of both the amount of rainfall and its distribution through the growing period.

Water-potential yield of common bean was relatively stable (1000 kg ha^{-1}), independent of total in-crop rainfall and soil conditions. Cowpea growth and development was, however, very responsive to in-crop rainfall. This is obvious as in wet years cowpea yield is very high (3000 kg ha^{-1}), whereas in drier years grain yields (>500 kg ha^{-1}) are even lower than common bean grain yields. Lablab yields instead, were fairly robust (1000 – 3000 kg ha^{-1}) and higher than those observed for common bean, even at low in-crop rainfall levels. Determined WUE in terms of biomass production was highest for cowpea and lablab (8 – 12 kg ha^{-1} mm^{-1} E_t) in comparison to common bean (6 – 8 kg ha^{-1} mm^{-1} E_t), but in terms of grain yield production only lablab (4 - 6 kg ha^{-1} mm^{-1} E_t) achieved higher values compared to common bean (3 - 5 kg ha^{-1} mm^{-1} E_t) and cowpea (2 - 4 kg ha^{-1} mm^{-1} E_t).

The magnitude of the soil impact on crop growth and development as well as water use and use efficiency differed with texture and water-holding capacity of the soil, soil evaporation and the interaction between these factors, rainfall pattern, crop canopy architecture and management.

The current results revealed that resource capture of the studied legumes was primarily outlined by their characteristic phenological development and further determined by phenological plasticity related to water deficit and the ability to respond to environmental conditions. Pronounced spatial and temporal differences in water use and use efficiency of the studied legumes were therefore first driven by the varying phenological development and secondly by species-specific morphological and physiological characteristics and mechanisms. However, the ability of the legumes to respond to environmental conditions and the degree of phenological plasticity have evolved different strategies to cope with challenging conditions in semi-arid areas. To consider the pronounced temporal and spatial differences in resource use and growth characteristics is fundamental to better design strategies for climate smart agriculture in the smallholder farming systems of Eastern Kenya. The calibrated and validated APSIM legume models can be used to make appropriate management decisions to provide smallholder farmers in semi-arid with alternative options to better integrate short-season legumes to improve the overall farm productivity and sustainability. Crop models such as APSIM allow to account for necessary complexity but at the same time manage to address high location specificity. This is particular important in diverse smallholder farming systems in semi-arid areas to adequately address their individual needs and opportunities. The variability in phenological development and resource use and use efficiency observed for the different legumes and their different adaption mechanism to semi-arid areas offer great potential for small-scale farming systems in challenging environments.

APSIM seems to be a great tool to explore their site-specific agricultural production potential and the impact of different management strategies is semi-arid Eastern Kenya. However, socio-economic constraints including labour requirements and market opportunities need to be assed in more detail to better channel agricultural recommendations to increase the possible adaption among farmers. Furthermore, long-term aspects of better integrated legumes towards improved farm sustainability and increased eco-efficiency need to be determined with the help of multidimensional whole farm analysis tools in order to proceed beyond crop and plot level in the future.

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Publications

Journal articles

Sennhenn A., Njarui D.M.G., Maass B.L., Whitbread A.: Considering effects of temperature and photoperiod on growth and development of Lablab purpureus (L.) Sweet in the search of short-season accessions for smallholder farming systems (Experimental Agriculture; accepted 24.03.2016).

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Whitbread A.M., **Sennhenn A.,** Grotelüschen K. (2013). Nitrogen-use-efficiency in maize-based farming systems in Malawi: a simulation study and meta-analysis of literature. Final Report to Dfid commission project 'Evaluation of the Government of Malawi's Farm Input Subsidy Programme (FISP).

Conference contributions

Sennhenn A., Njarui D.M.G., Maass B.L., Whitbread A. (2015). Can short-season grain legumes contribute to more resilient and productive farming systems in semi-arid Eastern Kenya? Oral presentation at the conference Agriculture and Climate Change – Adapting crops to increased uncertainty, February 15 – 17, 2015, Amsterdam, Netherlands.

Sennhenn A., Odhiambo J.J.O., Maass B.L., Whitbread A. (2014): Considering the effects of temperature and photoperiod on the growth and development of lablab (Lablab purpureus L.) in the search for short-season accessions for smallholder farming systems. Poster presented at Tropentag 2014 "Bridging the gap between increasing knowledge and decreasing resources", September 17 - 19, 2014, Prague, Czech Republic.

Grotelüschen K., **Sennhenn' A**., Njarui D.M.G., Maass B.L., Whitbread A. (2014): *Lablab purpureus*: A promising multi-purpose legume for enhanced drought resistance in smallholder farming systems of Eastern Kenya. Poster presented at Tropentag 2014 "Bridging the gap between increasing knowledge and decreasing resources", September 17 - 19, 2014, Prague, Czech Republic.

Sennhenn A., Njarui D.M.G., Maass B.L., A.M. Whitbread A. (2013): Finding strategies to mitigate drought stress in grain legumes in semi-arid Eastern Kenya. Poster presented at Tropentag 2011 "Development on the margin", September 15 - 17, 2011, Hohenheim, Germany.

Grotelüschen K., **Sennhenn A.**, Whitbread A., Dorward A. (2013): Nitrogen-use-efficiency in maize-based farming systems in Malawi: a simulation study and meta-analysis of literature. Poster presented at Tropentag 2011 "Development on the margin", September 15 - 17, 2011, Hohenheim, Germany.

Sennhenn A., Odhiambo J.J.O., Njarui D.M.G., Maass B.L., Whitbread A. (2012): Finding niches for drought tolerant, short-season lablabs in semi-arid farming systems of Eastern Africa. Poster presented at the Integrated Soil Fertility Management in Africa Conference, October 22 – 26, 2012, Nairobi, Kenya.

Sennhenn A., Prinz K., Whitbread A., Gebauer J., Rohde E., Jamnadass R., Kehlenbeck K. (2012): Morphological and molecular classification of local mango varieties in Kenya as a prerequisite for conservation of their genetic resources. Poster presented at Annual Conference of the Society for Tropical Ecology 2012 “Islands in land- and seascape”, February 22 - 25, 2012, Erlangen, Germany.

Kehlenbeck K., Rohde E., **Sennhenn A.**, Njuguna J.K., Omari F., Finyange, P., Wasilwa L., Jamnadass R. (2012): Mango production in Kenya: Opportunities and challenges along the value chain. Presented at the 2nd All Africa Horticulture Congress, Janurary 15 - 20, 2012, Skukuza, Kruger National Park, South Africa.

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Sennhenn A., Gebauer J., Omari F., Rohde E., Kehlenbeck K. (2011): Varietal diversity of local mangos in Kenya: a characterisation and identification approach. Poster presented at Global Conference on Augmenting Production and Utilization of Mango: Biotic and Abiotic Stresses. Session 1: Diversity of mango and its adaptability; June 21-23, 2011, Lucknow, India.

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February 2012 - November 2015 **Georg-August University Göttingen, Germany**
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- Doctor scientiarum agrariarum (Dr. sc. agr.)
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October 2006 - September 2009 **Leibniz Universität Hannover, Germany**
- Plant Biotechnology B.Sc.
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Practical experience

February 2012 - ongoing	**Georg-August University Göttingen, Germany** Department for Crop Science/ Crop Production Systems in the Tropics ▪ Research Assistant
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June - September 2009	**Boyce Thompson Institute for Plant Research, Ithaca, USA** ▪ Internship in the field of molecular plant research ▪ Cloning of aphid genes (*Myzus persicae*), transformation of *Arabidopsis thaliana* und *Nicotiana tabacum* ▪ *DAAD-RISE scholarship*
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August - September 2007	**Ministerio Agropecuario y Forestal (MAG-FOR) Jinotepe, Carazo, Nicaragua** ▪ Internship in the agricultural sector ▪ Monitoring of pests and diseases in dragon fruit plantations, training of farmer about plant protection techniques, logistics and distribution of seed material among farmers
August 2005 - July 2006	**APRODIM, San Marcos, Carazo, Nicaragua** ▪ Internship development aid/ agricultural sector ▪ Support of the agricultural project PIA (Proyecto Integral Agroecológio) ▪ Presentation of alternatives for land use in field training and workshop; e.g. living fences and home gardens

Declaration

D E C L A R A T I O N S

1. I, hereby, declare that this Ph.D. dissertation has not been presented to any other examining body either in its present or a similar form. Furthermore, I also affirm that I have not applied for a Ph.D. at any other higher school of education.

Göttingen, ...

.....
(Signature)

.....
(Name in block capitals)

2. I, hereby, solemnly declare that this dissertation was undertaken independently and without any unauthorized aid.

Göttingen,.....

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(Signature)